Impact of logging on aboveground biomass stocks in lowland rain forest, Papua New Guinea

Jane Bryan,[1,2,4] Phil Shearman,[2,3] Julian Ash,[3] and J. B. Kirkpatrick[1]

[1]*School of Geography and Environmental Studies, University of Tasmania, Private Bag 78, Hobart, Tasmania, Australia, 7001*
[2]*UPNG Remote Sensing Centre. P.O. Box 320, Biology Department, University of Papua New Guinea, Waigani,*
Port Moresby, Papua New Guinea
[3]*Research School of Biology, The Australian National University, Linnaeus Way, ANU, Canberra, Australia, 0200*

Abstract. Greenhouse-gas emissions resulting from logging are poorly quantified across the tropics. There is a need for robust measurement of rain forest biomass and the impacts of logging from which carbon losses can be reliably estimated at regional and global scales. We used a modified Bitterlich plotless technique to measure aboveground live biomass at six unlogged and six logged rain forest areas (coupes) across two ~3000-ha regions at the Makapa concession in lowland Papua New Guinea. "Reduced-impact logging" is practiced at Makapa. We found the mean unlogged aboveground biomass in the two regions to be 192.96 ± 4.44 Mg/ha and 252.92 ± 7.00 Mg/ha (mean ± SE), which was reduced by logging to 146.92 ± 4.58 Mg/ha and 158.84 ± 4.16, respectively. Killed biomass was not a fixed proportion, but varied with unlogged biomass, with 24% killed in the lower-biomass region, and 37% in the higher-biomass region. Across the two regions logging resulted in a mean aboveground carbon loss of 35 ± 2.8 Mg/ha. The plotless technique proved efficient at estimating mean aboveground biomass and logging damage. We conclude that substantial bias is likely to occur within biomass estimates derived from single unreplicated plots.

Key words: aboveground biomass; degradation; logging impact; Papua New Guinea; selective logging; tropical rain forest.

Introduction

Degradation of tropical forests resulting from selective logging is one of the least accurately known contributors to global greenhouse-gas emissions. "Degradation" refers to reductions in forest biomass while still retaining sufficient canopy cover to be classified as "forest" (Defries et al. 2007). National and global estimates of selective logging activity and resulting carbon emissions are uncertain for two reasons. Firstly, the areas of tropical forest subject to logging have not been accurately mapped (Asner et al. 2009) or mapped with sufficient regularity. Secondly, biomass losses due to logging have usually been derived from limited plot data, or derived via various models from estimates of regional biomass and timber-extraction volumes (Houghton et al. 2009).

Selective logging may give the impression of being benign because of rapid canopy closure, but it has been shown to cause substantial and immediate reductions in forest biomass, with repeated logging cycles leading to further losses (Putz et al. 2008). Biomass loss occurs in the extraction of logs, wastage from felled trees, in the wood used in the construction of logging infrastructure, through collateral damage to surrounding trees, and through clearance for roads and skid trails. Although it is possible to monitor the area being degraded due to logging using remote sensing (Asner et al. 2005), satellite platforms are yet to be reliably used to determine biomass (Houghton et al. 2009). Consequently, we are still largely reliant on ground-based surveys to estimate biomass and the impacts of industrial selective logging in tropical rain forest.

Over the past 30 years there has been a substantial increase in the degradation of the forests of Papua New Guinea (PNG) as a result of logging (Shearman et al. 2009). The PNG logging industry operates under a code of practice that is based on generic reduced-impact logging (RIL) principles. The code states that harvesting is limited to commercial trees of a minimum diameter at breast height (dbh) of 50 cm, states that buffer zones be delineated along creek lines, prohibits logging on steep slopes (>25 degrees), mandates the creation of "setup" or coupe plans that locate and mark trees to be felled, and defines the locations of skid trails within a specified area prior to the initiation of logging. Logging operators are required to cut lianas and vines prior to felling. Local landowners have the option of maintaining up to 10% of a concession as protected areas, although this is rarely exercised. Compared with other tropical regions, forests in New Guinea are generally dominated by trees with small canopies and contain relatively low volumes of extractable timber, typically 10–20 m^3/ha (Hammermaster and Saunders 1995, SGS 2005, 2006, Shearman et al. 2009).

The most common ground-survey approach to measuring tropical forest biomass is the plot-inventory method. This approach quantifies biomass using plot inventories (usually 0.12–1.0 ha) in which aboveground biomass (AGB) is estimated by measuring all trees within the plot, usually including trunk diameter at breast height, tree height, harvested log lengths, and diameters. Allometric relationships are used to link these measurements to volume and biomass (e.g., Chave et al. 2005). Logging damage is estimated by the difference between pre- and post-logging biomass and/or by direct measurement of damaged biomass (Pinard and Putz 1996). This approach yields a precise measurement of forest biomass and/or logging impact in the area being measured.

Accurate measurement of forest plots is both labor and time intensive. If resources are limited and the area being measured large, the use of plots may result in few samples and potentially poor representation of the range of biomass values across the landscape (Houghton et al. 2009). Extrapolating estimates of forest biomass from precisely measured unreplicated plots to the landscape or regional scale is therefore problematic (Bryan et al. 2010). In PNG there are only a few estimates of unlogged forest biomass (Bryan et al. 2010, Fox et al. 2010), and most have been derived from single, small (usually ≤1 ha), unreplicated plots that have not been located according to an unbiased sampling regime (Bryan et al. 2010). Similar estimates of biomass stocks from logged permanent sample plots also exist (Fox et al. 2010), but no measurement of pre-logging biomass or harvest intensity was recorded at these locations. Consequently, there is little accurate data on the biomass impacts of logging in PNG.

An alternative approach to plot inventories is to obtain biomass estimates from plotless measurement of basal area, volume, and biomass (Bitterlich 1947, Grosenbaugh 1952, Whitmore 1984). Plotless measurement can be much faster than plot-based surveys, allowing numerous points to be sampled, and mean values can be estimated with narrow confidence limits. If time is limited, there is a trade-off between precision of measurement at the plot level and accurately representing the variability of the forest landscape within which a plot is located. Since our aim was to measure logging impact and forest biomass at the landscape scale, we used a multi-point plotless sampling of basal area (the Bitterlich "angle-count" method), combined with allometric relationships to estimate volume and biomass. Our substantive aims were to quantify forest biomass in logged and unlogged forest, and losses caused by RIL practices in PNG at the landscape scale.

METHODS

Study area

The Makapa timber concession covers ~311 000 ha of lowland rain forest in the Western Province of Papua New Guinea. The concession licensee, Innovision Proprietary Limited, provided us with their survey maps, data and logging records, and a forestry team to assist with our surveys. Daily temperatures range from 23° to 28°C, and mean annual rainfall is ~2850 mm with occasional water stress in the dry season (usually around August). The study area comprises low hills (~15–70 m altitude) that support diverse medium-crowned rain forest, and poorly drained valleys and swamps that are not logged. The hill soils are deeply weathered, strongly leached, acidic clays and laterites that provide low fertility for plants (plinthudults and paleudults: Bleeker 1983). During the 1997–1998 El Niño drought, fires burned unlogged forests to the south, though the study area was unburned. Further details and a map of the study area are contained in the Appendix.

Logging commenced in the concession in 1999, and has generally adhered to the Papua New Guinea (PNG) "code of practice" (Forest Trends 2006). By early 2009, 52% of the concession had been logged with an average harvest intensity of 10.7 m³/ha, and a total FOB ("free on board," i.e., no delivery charge) timber production of 1.39×10^6 m³. Prior to logging, large-scale maps are created specifying boundaries of each coupe or "setup" (~50–200 ha), roads and major skid tracks, excluded buffer zones along water courses, excluded slopes >25°, and any additional "protected areas" or exclusion zones that have been agreed to in the lease. Survey staff clearly mark these features in the forest, as well as all undamaged trunks ≥50 cm dbh of commercial species that should be harvested. Logging of each setup is undertaken by a contracted team with a chainsaw and a tracked bulldozer with 4.9 m blade to drag logs to landings on the roads (see Plate 1). The team is paid by log volume but subject to penalties for code infringements. Each setup usually has three log landings adjacent to the nearest access road. In November 2008 we selected two areas (North, 142.54° E, 7.58° S, and South, ~142.55° E, 7.65° S; Appendix: Fig. A1) about 20 km apart that included three setups that had been logged within the past year and three adjacent setups with similar forest type and topography (from Innovision surveys) that were unlogged but marked for logging. At the time of survey, the global financial crisis had caused a sharp decline in demand for timber and operations had been temporarily curtailed, so we rejected "before and after" comparisons in favor of comparing recently logged forest with adjacent unlogged forest.

Deforestation

We defined "deforested areas" as those from which both vegetation and topsoil had been removed due to construction of logging roads and adjacent log landings. We used Innovision maps, SPOT (satellite pour l'observation de la Terre), and Landsat ETM+ imagery to detect and measure the length of all roads in the study area. We estimated the deforested width by recording the horizontal distance from the midline of the road to the adjacent tree canopy (Haglof Vertex laser VL400

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Hypsometer [Haglof, Långsele, Sweden]) at 10-m intervals along ~330-m sections of roads adjacent to the 12 setups. From the product of average width and length we estimated the deforested area and expressed this as proportion of the study area. We estimated the average aboveground biomass (AGB) loss due to deforestation from the area deforested and the average AGB (Mg/ha) of unlogged forest.

Forest biomass

We surveyed the intact or degraded forest in each of the 12 setups by locating 30 (39 for one transect) sample points at 100-m intervals along two or more straight transects that traversed the loggable area, ensuring that each point was at least 100 m from deforested boundaries and any other transect. To minimize topographic bias, transect directions were preselected to be predominantly perpendicular to ridges and creeks, thereby also avoiding bias due to skid tracks being preferentially located on ridges. Every 10 m along transects we recorded whether there was a canopy gap overhead from which we estimated the average canopy cover on each transect. At each 100 m point a count and basal area estimate of all standing live trunks (A_t), were made with a dendrometer. We recorded tree species or genus, dbh (by circumference tape, adjusted for buttresses), and whether the tree was alive. Details of adjustments made for slope, buttress and borderline trees are given in the Appendix. The count and basal area (A_p) of standing palms and *Pandanus* were recorded separately. We measured the height (hypsometer) of palms and *Pandanus* but were generally unable to see the top of canopy trees because of the dense foliage. We therefore estimated tree height (H, m) by regression from dbh (D, cm) based upon measurements of 307 trees in areas where adjacent canopies had recently been felled (see supplementary methods). Typical wood densities for each tree species or genus (ρ_s) were obtained from Eddowes (1977) and the ICRAF database.

We used the measured heights of palms and *Pandanus* to estimate their average height (H_p, m). At each survey point, we estimated the combined aboveground volume (m³/ha) of trees, using a paraboloid coefficient (0.5; e.g., Whitmore 1984), as $V_t = 0.5A_tH_t$, and of palms and *Pandanus*, using a cylindrical coefficient (1.0; e.g., Brown 1997), as $V_p = A_pH_p$. Total aboveground volume (V, m³/ha) was $V = V_t + V_p$. We estimated average aboveground density (P) at each point as the product of species density (ρ_s) and the proportion of the volume (V) present in that species. We estimated AGB (B, Mg/ha) at each point as $B = P \times V$.

Spatial variation in biomass was examined using a standardized variogram that shows how the distance between two sampled points influences the correlation between their biomass. High R^2 values indicate that biomass is relatively similar at that sampling distance. We estimated R^2 by ANOVA ($R^2 =$ model SS/total SS, ~[correlation]²) for biomass at various distances be-

tween pairs of sample points: (1) at 100 m intervals to 1500 m (each distance $n = 30$ pairs) along each of the 12 transects; and (2) among all points on different logged or unlogged transects (a) within the two regions (~5000 m distance, three randomizations of $n = 90$ points) and (b) between the regions (~20 000 m distance, three randomizations of $n = 180$ points).

RESULTS

We found the average road width to be 39.33 ± 1.5 m (mean ± SE; $n = 396$ roads). Across ~750 km² in the North and South combined, there was 0.052 ha of road per hectare of forest, or 5.2% ± 0.20% of the area deforested. We measured a total of 4455 trees, with the most common single species being the dipterocarp *Vatica rassak* at 16%; *Myristica* sp., *Canarium indicum*, and *Pometia pinnata* amounted to 4–5% each).

ANOVAs of point basal area, average tree height, average wood density and biomass at the regional and transect (nested within region) scales indicate substantial differences between unlogged and logged forest (see Appendix: Table A1 for full ANOVA table). Unlogged forest differed significantly at both transect and regional level for all parameters, with substantial regional variation in basal area, tree height, and biomass; and logging reduced the difference (Appendix: Table A1). Means and standard errors (SE) for all parameters and transects are shown in Table 1, each transect had 30 points, except for transect 6, which had 39 points.

In the North, the average AGB was reduced from 192.96 to 157.03 Mg/ha (18.6% reduction) by degradation (felling and skidding) and to 146.92 Mg/ha (23.9%) by degradation plus deforestation (including road-building); in the South, AGB was reduced from 252.41 Mg/ha to 171.97 Mg/ha (31.9%) by degradation and to 158.84 Mg/ha (37.1%) by degradation plus deforestation. Overall, we estimated the average unlogged forest biomass at Makapa was 222.68 ± 4.69 Mg/ha (mean ± SE), and the aboveground biomass killed by degradation plus deforestation averaged 69.81 ± 5.68 Mg/ha, or 31.35% ± 2.55%; Table 1. Expressed as carbon this is 35 ± 2.8 Mg/ha. The area of canopy gaps increased from 2.22% ± 0.41% in unlogged forest to 18.04% ± 1.04% in degraded forest and 23.24% ± ~1.2% including the deforested areas. Canopy gap measured from all transects is shown in Appendix: Table A1.

The spatial variogram (Appendix: Fig. A2) shows that R^2 values vary with distance and generally decline as distance increases, indicating that point biomass is less correlated at greater sampling distance. Individual transects show significant ($P < 0.05$) R^2 fluctuations with point separation but the fluctuations differ in each transect suggesting that each forest coupe differs in average spatial structure. The overall trend with distance was best modeled by power regression, indicating that the correlation declines rapidly at smaller distances and more slowly at larger distances (Appendix: Fig. A2). The correlation at 100 m (adjacent points: $R^2 = 0.56$) was

TABLE 1. Basal area, tree height, wood density, and aboveground biomass (AGB) in unlogged transects, and in logged transects subject to felling and skidding only ("degraded") and (final column) subject to felling, skidding, and road-building ("deforested"), in the Makapa concession in lowland Papua New Guinea.

Region (transect)	Basal area (m²/ha)		Height (m)		Density (Mg/m³)		AGB, degraded (Mg/ha)		AGB, deforested (Mg/ha)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
North unlogged (1)	29.72	0.95	24.79	0.36	0.513	0.009	191.22	7.36	191.22	7.36
North unlogged (2)	29.89	0.84	25.48	0.34	0.512	0.009	196.67	5.41	196.67	5.41
North unlogged (3)	27.31	0.85	24.93	0.44	0.558	0.014	191	9.87	191	9.87
Average	28.97	0.52	25.07	0.22	0.528	0.007	192.96	4.44	192.96	4.44
North logged (4)	22.16	1.05	26.05	0.37	0.536	0.01	153.46	6.56	143.22	6.12
North logged (5)	20.1	1.18	24.57	0.49	0.534	0.014	136.24	9.07	126.06	8.39
North logged (6)	25.67	1.02	25.51	0.3	0.536	0.012	175.78	8.32	165.83	7.84
Average	22.92	0.67	25.39	0.23	0.532	0.006	157.03	4.89	146.92	4.58
South unlogged (7)	37.27	1.48	27.2	0.29	0.544	0.007	275.64	12.06	275.64	12.06
South unlogged (8)	29.72	0.92	25.03	0.33	0.556	0.007	205.02	6.85	205.02	6.85
South unlogged (9)	39.25	1.41	25.91	0.3	0.534	0.007	276.57	11.97	276.57	11.97
Average	35.41	0.86	26.04	0.2	0.545	0.004	252.41	7	252.41	7
South logged (10)	26.54	1.18	25.65	0.32	0.546	0.008	183.03	8.2	168.69	7.56
South logged (11)	26.2	0.94	24.7	0.39	0.519	0.006	167.17	6.19	156.5	5.8
South logged (12)	23.02	1.16	26.08	0.39	0.54	0.008	165.72	9.8	151.33	8.95
Average	25.25	0.65	25.48	0.22	0.535	0.004	171.97	4.51	158.84	4.16
Average unlogged	32.19	0.55	25.55	0.15	0.536	0.004	222.68	4.69	222.68	4.69
Average logged	24.03	0.47	25.43	0.16	0.534	0.004	164.15	3.45	152.88	3.21
Unlogged − logged	8.11	0.72	0.12	0.22	0.003	0.006	58.18	5.82	69.81	5.63
Difference (%)†	25.19	2.24	0.47	0.86	0.56	1.12	26.13	2.61	31.35	2.53

Note: Each transect had 30 points at which measurements were taken, except for transect 6, which had 39 points.

† Difference between average logged and average unlogged forest as a percentage of unlogged forest.

higher than the regression estimate, partly due to patchy logging impacts.

DISCUSSION

The Makapa concession has been found to be one of the most law-abiding logging projects in Papua New Guinea (PNG) (Forest Trends 2006). Greater biomass damage is likely to occur in other concessions, such as the neighbouring Wawoi Guavi Blocks where machinery has been used to repeatedly log the same areas within the last 15–20 years and/or where local sawmills (or veneer mills) are present and trees <50 cm dbh are harvested to supply them (Forest Trends 2006). In addition, greater biomass damage is likely to occur in forests that contain a higher biomass and standing stock. Our findings of a 24% and 37% reduction of aboveground biomass (AGB) caused by reduced-impact logging (RIL) in the North and South, respectively, should therefore be viewed as conservative estimates for PNG logging operations.

The mean AGB of all 17 published small-plot inventories in lowland forest in PNG is 274 Mg/ha (Bryan et al. 2010, Fox et al. 2010), higher than mean AGB at Makapa (223 Mg/ha). The small plot size, limited number, and likely locational bias of these previous estimates make it difficult to confidently assert whether AGB at Makapa is low for PNG, or indeed typical. Nevertheless, the biomass of forests at Makapa is probably limited by low soil fertility, which is indicated by the presence of nitrogen-fixing *Gymnostoma* and legumes. Windblown volcanic ash has an important role in boosting soil fertility in PNG, and this generally declines across the southern lowlands where Makapa is located (Bleeker 1983). It is also possible that fires, similar to those in nearby forests during the 1997–1998 El Niño drought, burned the sampled forests a few hundred years ago and maximum biomass has not been reached everywhere.

The biomass variogram (Appendix: Fig. A2) shows the bias that may occur from local or plot sampling: on average, closer points had more similar biomass. Though the 100-m spacing (adjacent points) was sufficient to avoid overlap in the trees that were sampled, their biomass correlation is indicative that they share similar habitat, past disturbance, and/or recent logging activity. At greater distances (to >20 km) the average correlation declined over scales corresponding to topographic variation across the landscape. Overall, there was no optimum sampling distance; rather, dispersed sampling reduced the bias that would arise from local sampling, especially at ≤100 m (~1-ha plot scale). Little attention has been given to the issue of spatial variation when sampling rain forests (we are not aware of a comparable analysis), and it is apparent that a single small plot (e.g., 1 ha, which is commonly used) is liable to large bias. Such plots may be more suitable for monitoring site-specific change rather than estimating the biomass of large forested areas. For example, it would be possible to obtain AGB estimates anywhere between 50 and 450 Mg/ha if biomass was surveyed from a single small plot located at a small number of the 396 points that we surveyed (Appendix: Fig. A3). This result strongly supports our choice of dispersed point sampling.

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Randomly located sample points across the region are theoretically optimal, but travelling time was a major constraint and we estimated that one team (~4 people) could only sample 2–3 random points each day rather than 30 points along a single transect. Our transect method was rapid and provided many point measures, allowing an estimate of the mean biomass with a low standard error. Since transects varied significantly it was important that these were adequately replicated across the region. Buttresses were common on large trees so observation above buttresses plus adjustment for this height and taper are necessary: our trigonometric adjustment was an effective and simple field solution (see Appendix). The Bitterlich (1947) survey method relies on unobstructed visibility at breast height and we noted that while this was possible in mature and recently (≤ 1 yr) logged forest, it could be difficult in regenerating forest a few years after logging. Individual allometric relationships between dbh, height, volume, and wood density for each species could improve the precision of biomass estimates (Clark et al. 2001) however it is not likely that this would substantially alter the point or average biomass since most stands comprise a diverse mixture of species.

In unlogged forest, basal area, average tree height, and average wood density all varied significantly between transects and regions (Table 1; Appendix: Table A1). The causes of variation were, in decreasing order, basal area, height, and density, suggesting that the development of the stands (basal area largely reflects the abundance of larger trees) was more influential than their intrinsic fertility (usually correlated with canopy height) or composition (that can affect average density). The southern region generally had more large trees, possibly due to a longer period without disturbance. Logging reduced all the differences between regions and transects such that, at the regional level, only a minor significant difference in basal area remained. Much of the regional difference in unlogged forest structure is probably due to the large trees that are removed by logging. While logged forests were more similar at the regional level, minor but significant differences remained in basal area and height among transects (~setups) suggesting that the forest and/ or logging activity varies at this scale. Since a different team logged each setup, we could not determine the cause of the difference. Average tree height varied little (~0.1 m) within unlogged forest and between unlogged and logged forest. For this reason remote-sensing techniques that aim to measure only tree height (e.g., from lidar and radar) may be of limited use for estimating biomass losses from logging. This emphasizes the need for fast and reliable ground-survey methods.

The higher-biomass forest in the South had a greater proportional reduction in biomass than did the lower biomass forest in the North. This trend is also present when our findings are compared to those from a logging-impact study in climatically similar, but higher biomass rain forest in Sabah, Malaysia (Fig. 1). The reported logging regimes in Sabah included unregulated "conventional" logging, and RIL similar to Makapa except that the harvest threshold was larger (>60 cm dbh). These two regimes effectively bracket logging practices at Makapa. PNG logging is also comparable to that at Sabah because Malaysian companies dominate the PNG industry. Unlogged biomass (~320 Mg/ha, above-ground live-tree biomass) and the proportional reduction in standing biomass (37% for RIL, 58% for conventional), excluding road-building, were both higher than at Makapa (18.6% in the North, and 31.9% in the South), but were consistent with the trends we measured. This suggests that biomass killed by logging is not a fixed proportion of unlogged biomass, but rather higher-biomass forests have proportionally greater biomass killed (Fig. 1). It also means that plot inventories measuring live AGB remaining after logging (e.g., Fox et al. 2010) cannot alone provide accurate estimates of biomass killed by logging. Some measure of either pre-logging biomass, logging practices, or damage at the same locations is also needed.

Apart from lower unlogged biomass stocks and different dbh thresholds, the biggest difference between RIL at Makapa and at Sabah is in harvesting intensities, and consequently the proportion of total killed-tree biomass contained in the harvested timber. At Makapa, harvesting intensities (10.7 m^3/ha) and unlogged biomass (193 and 252 Mg/ha) represent the lower end of tropical forest potential, and the ratio of killed biomass to harvest was high, ranging from 9.4 (46.0 Mg/ha ÷ 4.9 Mg/ha) in the North to 18.6 (93.6 Mg/ha ÷ 5.0 Mg/ha) in the South. In the higher-biomass forests at Sabah (~320 Mg/ha), where harvest intensities represent the upper range possible from tropical selective logging, the ratio of killed AGB tree biomass to timber harvest (assuming 5.2% damage from road-building) ranged from 2.6 (134.5 Mg/ha ÷ 51 Mg/ha) using RIL to 3.2 (206.9 Mg/ha ÷ 64.4 Mg/ha) using conventional logging (Pinard and Putz 1996). Measurements of coarse woody debris in logged forest in Brazil indicate that conventional logging results in 6.8 times (68 Mg/ha ÷ 10 Mg/ha) to 10 times (100 Mg/ha ÷ 10 Mg/ha) as much total killed biomass as is contained in the harvested timber (Keller et al. 2004, Asner et al. 2005). Live biomass in Brazil was not directly measured, although pre-logging biomass is reported as about 282 Mg/ha (Keller et al. 2004), intermediate between Makapa and Sabah. Such variation in the damage-to-harvest ratios indicates that policies to reduce wasteful carbon emissions associated with logging should address not just improving logging practices (e.g., RIL) but also the avoidance of forests in which low yields will inevitably cause a high ratio of damage to harvest.

Since harvested log volume is commonly recorded as a measure of yield and for royalties, it would be convenient to use this to predict total killed biomass, however, the relationship varies strongly with both logging practices (RIL vs. conventional) and unlogged forest biomass. If logging practices are equivalent,
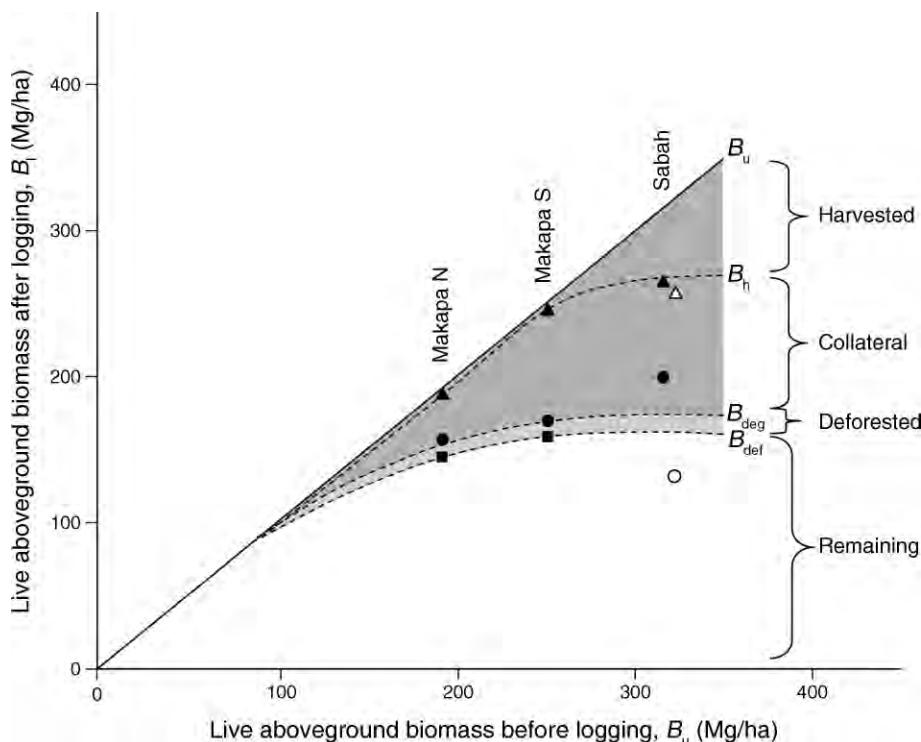
FIG. 1. Stylized representation of aboveground biomass (B) measured in two regions, north (N) and south (S), at Makapa concession, lowland Papua New Guinea, before and after logging (B_u [unlogged] and B_l [logged], respectively). Measurements of pre- and post-logging biomass (aboveground live-tree biomass only) from conventional logging (white symbols) and RIL (reduced-impact logging; black symbols) at Sabah, Malaysia, are shown for comparison (Pinard and Putz 1996). These two logging regimes effectively bracket logging practices at Makapa.

B_l is represented by two sets of points: aboveground biomass after degradation, B_{deg} (all felling and skidding, of which a fraction is harvested and a fraction is collateral damage), shown as circles; and aboveground biomass after degradation and deforestation (including road-building), B_{def}, shown as squares. Triangles represent B_u less harvested biomass (B_h) only. The biomass curves were approximated by positive values of the polynomial regression equations:

$$B_{deg} = B_u - 3.12065 - 0.3137B_u + 0.002875B_u^2 - 0.000001575B_u^3$$

$$B_{def} = B_u - 1.7302 - 0.2348B_u + 0.002742B_u^2 - 0.000001514B_u^3$$

$$B_h = 0.000019B_u^3 + 0.009749B_u^2 - 0.621873B_u + 83.571816.$$

Light gray shading indicates biomass killed by deforestation; darker gray shading represents the fraction killed through degradation. Measured biomasses at Sabah after RIL and conventional logging bracket that predicted from the Makapa measurements (B_{deg}).

trends with unlogged biomass could be summarized by a regression relationship, although more measurements are needed (Fig. 1). Yet logging practices vary greatly. Total killed biomass in Brazil (68–100 Mg/ha), is lower than predicted from Makapa and Sabah for a forest of 282 Mg/ha (Fig. 1). Such differences may result from inherent differences in the proportion of trees that are harvestable due to defects or species, demand for different tree sizes, differences in logging rules or technique, or differences in the method of estimating parameters. At Makapa, the percentage canopy gap (23.24%) after RIL was closer to canopy gap caused by conventional logging in Brazil rather than RIL (Asner et al. 2004), suggesting differences in harvesting. However,

in PNG (this study) and Malaysia (Pinard and Putz 1996) ground surveys measured standing biomass, whereas the Brazil (Keller et al. 2004, Asner et al. 2005) surveys measured only the killed component. Clearly there is a need to establish if there are biases among the methods. Since the outcomes vary with both unlogged forest biomass and the logging practice, we favor techniques that measure both together, such as the Bitterlich (1947) approach that could also be used to efficiently record fallen debris.

The Makapa timber concession was allocated an annual allowable cut of 170 000 m³ per annum, which, based on a 35-year cutting cycle, suggests an original estimate of a total of 5.95×10^6 m³ of merchantable

PLATE 1. Logging operations in the Makapa concession, Papua New Guinea. From top left clockwise: an arial view of logging roads as seen in a 2005 SPOT satellite image (top left), and aerial photography (top right); on-ground view of bulldozers on a logging road; log pond; skid trail; and a logging road. Photo credits: J. Ash and P. Shearman.

timber. On the basis of the average harvesting yield extracted across the whole of Makapa concession to 2009 (10.7 m³/ha) it is likely that Makapa only ever contained ~2.58 × 10⁶ m³. The designated annual allowable cut (assuming 1/35th of the total merchantable volume in the concession) therefore overestimated timber volume in Makapa by 230%. In other PNG logging concessions it is likely that merchantable volume has also been overestimated, leading to a much greater area being logged per annum than ought to be occurring if the 35-year cutting cycle was to be observed. Additionally, overestimation of annual allowable ex-

traction volumes creates pressure to meet the annual target not only by increasing the annual logged area, but by intensifying logging or by premature second harvests in logged-over forest. This may partly explain why the average life of an active concession in PNG has been closer to 11 years, rather than 35 years (Katsigris et al. 2004, Shearman et al. 2008). The overestimation of merchantable volume in Makapa was not principally caused by inadequacies in the Forest Inventory Mapping System (Hammermaster and Saunders 1995) used by the management authority, as this provides a comparable estimate to actual harvest data.

The 35-year concession lease in PNG was based on the notion that rainforest can support a 35-year logging cycle indefinitely and sustainably. However, elsewhere in the tropics, timber stock recovery over cutting cycles of 35 years has not been possible using comparable RIL harvesting (Putz et al. 2008). In PNG these problems have been exacerbated by overestimation of the potential yield of a concession that has created an incentive to intensify logging or undertake repeat harvests within the cutting cycle. Reform of the process of allocating annual allowable harvest volumes to logging concessions in PNG is needed.

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APPENDIX

Details of study area, basal-area survey adjustments, tree height–dbh regression, frequency distribution of point biomass estimates, standardized variogram for point biomass sampled at various distances, full ANOVA table for transects nested within region, and canopy gap recorded at each transect (*Ecological Archives* A020-078-A1).

Communications