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Estimating rainforest biomass stocks and carbon loss from deforestation and degradation in Papua New Guinea 1972–2002: Best estimates, uncertainties and research needs

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A B S T R A C T

Reduction of carbon emissions from tropical deforestation and forest degradation is being considered a cost-effective way of mitigating the impacts of global warming. If such reductions are to be implemented, accurate and repeatable measurements of forest cover change and biomass will be required. In Papua New Guinea (PNG), which has one of the world's largest remaining areas of tropical forest, we used the best available data to estimate rainforest carbon stocks, and emissions from deforestation and degradation. We collated all available PNG field measurements which could be used to estimate carbon stocks in logged and unlogged forest. We extrapolated these plot-level estimates across the forested landscape using high-resolution forest mapping. We found the best estimate of forest carbon stocks contained in logged and unlogged forest in 2002 to be 4770 Mt (±13%). Our best estimate of gross forest carbon released through deforestation and degradation between 1972 and 2002 was 1178 Mt (±18%). By applying a long-term forest change model, we estimated that the carbon loss resulting from deforestation and degradation in 2001 was 53 Mt (±18%), rising from 24 Mt (±15%) in 1972. Forty-one percent of 2001 emissions resulted from logging, rising from 21% in 1972. Reducing emissions from logging is therefore a priority for PNG. The large uncertainty in our estimates of carbon stocks and fluxes is primarily due to the dearth of field measurements in both logged and unlogged forest, and the lack of PNG logging damage studies. Research priorities for PNG to increase the accuracy of forest carbon stock assessments are the collection of field measurements in unlogged forest and more spatially explicit logging damage studies.

1. Introduction

The contribution of tropical logging and deforestation to global greenhouse gas emissions has been regarded one of the most uncertain components of climate change models (IPCC, 2007; Houghton, 2003). Despite this uncertainty, the reduction of emissions from deforestation and degradation (REDD), especially in the tropics, has been seen as a cost-effective way of reducing global greenhouse gas emissions (Stern, 2007). Degradation refers to the reduction in forest biomass through a variety of processes, especially through logging, whilst retaining sufficient tree cover to still be classified as 'forest' (Defries et al., 2007). As REDD is likely to form part of a binding United Nations (UN) international agreement aimed at mitigating the impacts of global warming (Gibbs et al., 2007), it is critical that uncertainty in regard to forest-related emissions is reduced.

There are two broad approaches to estimating both the amount of biomass stored in tropical forests and the rate at which these stocks are being depleted: approaches that model ecosystem processes and approaches that extrapolate field measurements (Brown, 1997; Clark, 2007; Defries et al., 2007; Ju et al., 2007; Wang et al., 2007). Here we examine the field-based approach. This approach for estimating tropical forest carbon stocks and losses is to measure forest area, the area of forest loss over time, and the amount of biomass stored per unit area of forest or lost per unit area of deforestation or degradation (Brown, 1997; Achard et al., 2002; Houghton, 1999; Houghton, 2003; FAO, 2005). The two largest issues contributing to uncertainty relate to the accuracy of mapping the extent of logged and unlogged forest, and the

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measurement of biomass and biomass losses within both these zones (Houghton et al., 2001).

Commonly cited global tropical emissions estimates have relied upon FAO data for estimates of forest area, rates of forest loss and rates of wood harvest (Houghton, 1999, 2003; Stern, 2007; IPCC, 2007). These FAO forest data, supplied by national governments, have been shown to be inconsistent in quality between countries, and the spatial resolution of their mapping is often too coarse to accurately measure forest change (Grainger, 2008). The issue of data resolution is especially important in the measurement of degradation. Logging-related degradation in the tropics can only be detected using high-resolution remote sensing imagery (Asner et al., 2002; Shearman et al., 2009). Globally, as the area of logged forest is at least as large as the deforested area, and as carbon emissions from logging-related degradation are substantial (Nepstad et al., 1999; Asner et al., 2005; Shearman et al., 2009), the use of coarse and moderate scale satellite imagery which cannot detect logging at all, will necessarily underestimate tropical emissions and overestimate tropical carbon stocks.

The estimation of carbon stocks and their depletion by logging requires not only area data, but also data on the carbon content of logged and unlogged forests. Carbon contained in tropical forest biomass is usually calculated by estimating biomass from full tree censuses of forest plots using allometric equations and extrapolating these measurements to a regional or national scale using remotely sensed or other regional mapping information (Brown, 1997; Houghton et al., 2001; Defries et al., 2007; Gibbs et al., 2007; Malhi et al., 2006; Saatchi et al., 2007). Loss of carbon stocks through logging is usually derived from logging damage studies, also generally obtained from plot data (Houghton, 1999; Houghton, 2003). Plot data suitable for these calculations are scarce and seldom distributed in a representative manner at the national scale (Gibbs et al., 2007). Carbon losses from logging have also been calculated by 'scaling up' log-extraction volumes (Asner et al., 2005) and by the use of radar or lidar data (Chambers et al., 2007; Hurtt et al., 2004; Drake et al., 2003). However, log-extraction data are usually poor and both radar and lidar rely upon calibration using field measurements which themselves have usually been obtained from a small number of small plot inventories (Chambers et al., 2007; Hurtt et al., 2004; Drake et al., 2003).

The extent of both logged and unlogged forest in Papua New Guinea (PNG) has been mapped at a high resolution, and the area of forest cleared and degraded between 1972 and 2002 has been measured (Shearman et al., 2009). Between 1972 and 2002, a net 15% of PNG's 1972 forest extent was cleared and 8.8% degraded due to logging, and by 2002 the rate of forest change (deforestation and degradation) was approximately 1.4%/year (Shearman et al., 2009). The primary drivers of this change were industrial logging and subsistence-related activities with minor contributions from forest fires, industrial agriculture and mining. In 2002 there were 25,332,253 ha of unlogged forest, and 2,919,714 ha of logged forest. Thus in PNG uncertainty associated with the forest mapping component of estimating tropical forest emissions has been greatly reduced.

However, the other major sources of uncertainty in estimating carbon stocks and fluxes, the measurement of forest biomass and biomass losses associated with logging, remain unaddressed. Although the island of New Guinea, the eastern half of which is PNG, contains one of the world's largest areas of extant tropical forests (Brooks et al., 2006), there have been few published measurements of forest biomass (Edwards and Grubb, 1977; Ash, 1988; Enright, 1979), and fewer still of biomass removal due to logging (Abe et al., 2000). Prior to the present work, there have been no studies which attempt to collate and integrate PNG-specific measurements of forest biomass stocks and losses with high-resolution forest mapping. This is a necessary precursor to improve upon generic estimates of PNG's forest-related emissions which have been derived almost entirely from non-PNG biomass measurements (Achard et al., 2002; Houghton, 1999).

Here we aim to collate existing measurements of PNG biomass stocks and integrate these data with the existing high-resolution forest mapping and change measurements (Shearman et al., 2009) to produce estimates of forest carbon stocks in 2002 and carbon emissions from deforestation and degradation between 1972 and 2002. We identify the key areas in which PNG lacks critical information as well as highlighting the difficulties of estimating forest carbon stocks – a challenge that will need to be overcome globally to address REDD-related requirements. We also provide a list of research and data acquisition priorities for PNG.

2. Materials and methods

PNG is located in the South Pacific, north of Australia and east of Indonesia. The nation of PNG consists of the eastern half of the island of New Guinea in addition to a number of smaller islands. The main island of PNG contains a series of rugged mountain ranges generally referred to as the 'Highlands' where the highest elevation is 4509 m, surrounded by a low elevation relatively flat 'lowland' region. Annual mean rainfall varies from 1000 mm to more than 8000 mm, and mean annual temperatures range from less than 3 °C to more than 27 °C, varying largely with elevation (McAlpine et al., 1983).

We estimated forest biomass and carbon stocks in PNG by following the approach of extrapolating field measurements of biomass across forest extent using forest mapping and environmental data (Brown, 1997; Houghton et al., 2001; Defries et al., 2007; Malhi et al., 2006; Saatchi et al., 2007). We estimated forest carbon losses (flux) through degradation and deforestation using the measured area that has been deforested and degraded in combination with extrapolated forest biomass measurements.

The data of Shearman et al. (2009) were used as the area component of our biomass extrapolation. This forest mapping was conducted using a semi-automated forest classification procedure using high-resolution (20–30 m) satellite imagery and aerial photography (Shearman et al., 2009). Accuracy of the forest mapping and change detection was high because the forest mapping was conducted at a scale where it is difficult for a trained human observer to be mistaken when viewing basic vegetation classes in high- and very-high-resolution imagery and aerial photography (Shearman et al., 2009). As this forest mapping focused on change in 'rainforest' only, and did not include dry evergreen forest, mangroves or woodland, we also confine our estimate of carbon stocks and losses to rainforest. Hereafter we use the term 'forest' to refer to 'rainforest'.

We collated 22 unlogged biomass measurements (Table 1), of which, two were obtained from published estimates of destructive harvesting of unlogged forest plots (Edwards and Grubb, 1977; Abe et al., 2000), 6 from published estimates derived from forest plots (Ash, 1988), two average biomass measurements from ~3000 ha (Bryan et al., submitted), and one average biomass measurement from approximately 100 ha (Shearman, unpublished data). Although Enright (1979) reports the AGB in a stand of *Araucaria* forest as 286 t/ha, we have not included this measurement as Enright (1979) used an allometric equation developed in mixed montane forest (Edwards and Grubb, 1977) that did not include tree height. As *Araucaria* are an exceptionally tall species, the allometric equation developed by Edwards and Grubb (1977) is likely to underestimate biomass.

Table 1
Biomass for forest plots across PNG.

Name	Biomass (t/ha)	Annual mean temperature (°C)	Reference
Mt Hagen mixed 1	375	8.3	Powell, 1970
Mt Hagen mixed 2	411	10.2	Powell, 1970
Mt Hagen mixed 4	493	12	Powell, 1970
Mt Hagen *Nothofagus* 5	458	12	Powell, 1970
Chimbu mixed	350	13	Edwards and Grubb, 1977
Finschaffen	597	26.3	Abe et al., 2000
Madang Ramu	320	27.5	G. Weiblen (unpublished data)
Mt Bosavi	311	23.8	Shearman (unpublished data)
Mt Missim	428	19.1	Pratt, 1983
Nothofagus pulleii	333	12.2	Ash, 1988
Nothofagus grandis	296	14	Ash, 1988
Mixed forest	180	13.4	Ash, 1988
Montane conifer	118	10.4	Ash, 1988
Mixed (*Nothofagus*) Kutubu limestone	270	21.9	Ash, 1988
Mixed (*Nothofagus*) Kutubu volcanics	378	23.1	Ash, 1988
Vanimo 1	414	28.4	Cameron and Vigus, 1993
Vanimo 2	441	28.4	Cameron and Vigus, 1993
Kapiura 1	328	28.3	Cameron and Vigus, 1993
Kapiura 2	361	28.3	Cameron and Vigus, 1993
Kumusi 1	479	28.1	Cameron and Vigus, 1993
Makapa 1	305	25.5	Bryan et al. (submitted)
Makapa 2	230	25.5	Bryan et al. (submitted)

In addition to published estimates of biomass we used 11 full tree censuses from across PNG which contained at a minimum, the diameter of all trees in a plot above a minimum diameter at breast height (dbh) of 10 cm, as well as species or genus information from which wood density estimates can be obtained. In practice, most forest plot inventories that were collated contained dbh, height and species or genus data.

We estimated above-ground biomass (ABG) for each tree contained in the 11 forest inventories using allometric equations developed for pan-tropical forest types using wood density as well as diameter and height if both were available, or diameter only where height was unavailable (Chave et al., 2005). AGB in tonnes per hectare in these 11 plots was calculated by the addition of the biomass of each tree in the plot followed by the division of the total tree biomass by the area of the plot.

Wood densities for each tree species were obtained from Eddowes (1977) and the International Centre for Research in Agroforestry (ICRAF) world agroforestry website (http://www.worldagroforestrycentre.org/sea/Products/AFDbases/WD). Where a 'high' and a 'low' wood density was reported for a particular species, the average density was used. Where 'high', 'medium' and 'low' values were reported, the 'medium' value was used. For trees which had been identified only to genus level, the average wood density of all species within that genus was used. This assumption was based on the work of Chave et al. (2006) who found when species level wood density information was unavailable, genus level was sufficient. A limited number of trees in all plots were unidentified, and in these cases the average wood density of all trees in the stand was used.

We applied a root to shoot ratio of 0.12 for lowland and 0.22 for montane forest (Brown, 1997) to each a biomass estimate which did not include below ground biomass to estimate total live tree biomass (Table 1).

There have been a number of studies, primarily of the Amazon, which use remotely sensed and other forest cover and environmental variables to extrapolate field measurements of biomass across the tropical landscape (Houghton et al., 2001; Malhi et al., 2006; Saatchi et al., 2007). Summing the biomass per unit area across the total forest area produces an estimate of forest biomass stocks. In PNG, the number of existing field measurements (22), is too small for a statistically robust multi-variable extrapolation (Adcock, 1997). However, in moist tropical evergreen forests forest productivity has been argued to be positively related to annual mean temperature without a corresponding increase in biomass turnover (Raich et al., 2006). We therefore tested for this relationship in our data set using linear, quadratic and polynomial regression.

Annual mean temperature at each forest measurement had either been recorded with the original tree measurements, or was obtained from a temperature surface we created by averaging Worldclim gridded 1 km mean monthly minimum and maximum temperature grids (Hijmans et al., 2005). The relationship between biomass plots and annual mean temperature is displayed in Fig. 1. There was no significant tendency in the relationship with any of linear, quadratic or polynomial fits, the best fit being linear ($R^2 = 0.04$, $p > 0.05$). Therefore, we applied the average biomass of all measurements as our best estimate of biomass in tonnes per hectare in unlogged forest. We multiplied the average biomass in unlogged forest by the area of unlogged forest obtained from the high-resolution map of forest area 2002. This formed our best estimate of biomass stocks in unlogged forest 2002.

To examine uncertainty associated with our best estimate of unlogged forest biomass stocks, we used the upper and lower 95% confidence intervals around the best estimate of unlogged biomass stocks (t/ha) to produce 'upper' and 'lower' estimates of unlogged biomass stocks. We multiplied the upper and lower biomass in unlogged forest (t/ha) by the area of unlogged forest obtained from the high-resolution map of forest area 2002. This formed our upper and lower estimate of biomass stocks in unlogged forest 2002.

Additionally, to assess uncertainty associated with our unlogged forest measurements, we compared our PNG measurement with biomass measurements from other tropical regions (Brown and Lugo, 1982; Malhi et al., 2006; Chambers et al., 2001; Chave et al., 2001, 2004; Takyu et al., 2003; Hoshizaki et al., 2004; Liddell et al., 2007). We applied a root to shoot ratio of 0.12 for lowland and 0.22 for montane forest (Brown, 1997) to each estimate that reported AGB only. We also plotted these pan-tropical biomass measurements against annual mean temperature to compare the biomass–temperature relationship with that found in PNG.

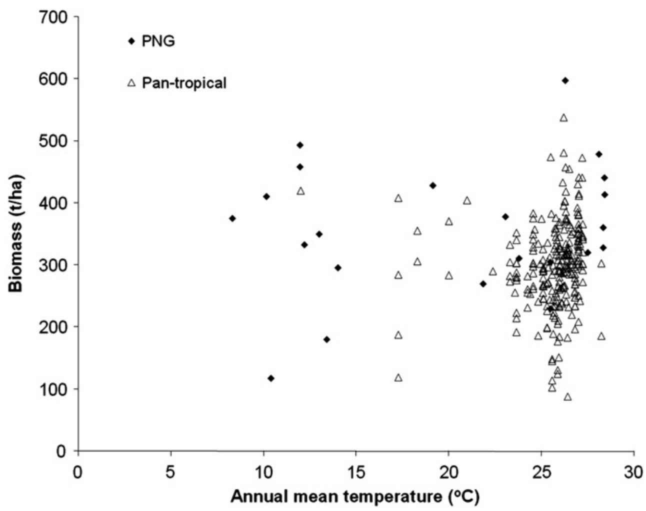

Fig. 1. The relationship between biomass and temperature from PNG biomass measurements (solid black circles) compared to measurements from other tropical countries (pan-tropical, triangles). There was no significant correlation between temperature and the PNG biomass measurements.

We estimated logged forest biomass using tree censuses in logged forest collected across PNG and extrapolated these estimates across the mapped area of logged forest in 2002. These measurements were derived from the first assessment of the permanent sample plots (PSPs) set up by the International Tropical Timber Organisation (ITTO) and are contained in the PINFORM growth model (Alder, 1998). As each PSP was measured a short time after logging, our estimate of logged forest biomass does not include either the further reduction of biomass occurring through residual death if logging was intensive or the slow accrual of biomass if logging was less intensive.

Each PSP contained a full tree census of the logged plot including species and/or genus, and dbh of all trees >10 cm dbh. We estimated AGB in each plot using the same method applied in the estimation of biomass in our unlogged full tree censuses described previously, using the allometric equations of Chave et al. (2005). We applied a root to shoot ratio (Brown, 1997) to each estimate of AGB to produce an estimate of total live tree biomass. There are 72 PSPs located mostly in pairs. The location of two of these plots was unclear from the documentation (Alder, 1998), so consequently they were excluded. We took the average of each pair as the biomass estimate of that location, resulting in 35 estimates of logged forest biomass. We calculated the average biomass in tonnes per hectare across all PSPs and then multiplied this value by the mapped area of logged forest in 2002. This formed our best estimate of the amount of biomass stored in PNG's logged forests in 2002.

To examine uncertainty associated with our best estimate, we also produced an upper and lower estimate of logged forest biomass stocks using the upper and lower 95% confidence intervals around the mean of our logged biomass measurements to produce 'upper' and 'lower' estimates of logged forest biomass stocks.

Finally we added our best estimates of logged and unlogged biomass together to produce a best estimate of PNG's rainforest biomass stocks in 2002. We also added our 'upper' estimates of logged and unlogged biomass stocks to produce an 'upper' estimate of rainforest biomass stocks in 2002, and added our 'lower' estimates to produce a 'lower' estimate of rainforest biomass stocks in 2002. To estimate carbon from biomass we multiplied our estimates of biomass stocks by 0.5, as approximately 50% of biomass is carbon (Brown and Lugo, 1982).

We estimated the amount of carbon released through deforestation and degradation between 1972 and 2002 using the high-resolution map of the area deforested and degraded over this period. To estimate biomass killed through deforestation, we multiplied the area deforested by our best estimate of unlogged biomass in tonnes per hectare. As the change analysis we used identified causes of deforestation, we also separated our best estimate of biomass killed through deforestation into logging-related deforestation, and non-logging-related deforestation.

To estimate biomass killed due to degradation, however, required an additional step of estimating potential unlogged biomass within the area degraded. This is because the PSP data we used to estimate logged forest biomass contained no pre-harvest inventory, nor a measure of the intensity of harvesting. Hence these plots alone could not provide an indication of biomass removed through logging (Cameron and Vigus, 1993). We therefore estimated gross biomass in tonnes per hectare killed due to logging-related degradation as the difference between our best estimate of unlogged biomass (t/ha), and our best estimate of logged forest biomass (t/ha). We then multiplied our best estimate of gross biomass (t/ha) killed due to logging-related degradation by the area degraded to estimate gross biomass (t) killed due to degradation 1972–2002.

To examine uncertainty in our best estimate, we produced 'upper' and 'lower' measures of gross biomass (t/ha) killed due to logging-related degradation. The 'upper' estimate was the difference between our 'upper' estimate of unlogged forest biomass stocks. The 'lower estimate was the difference between our 'lower' unlogged biomass and 'upper' logged forest biomass estimates. We then multiplied each of our upper and lower estimates of biomass (t/ha) killed due to logging by the area degraded to produce 'upper' and 'lower' estimates of gross biomass (t) killed due to degradation 1972–2002.

We added the amount of biomass removed through deforestation and through forest degradation and multiplied this value by 0.5 to estimate gross carbon lost between 1972 and 2002 for each of our best, upper and lower estimates.

Shearman et al. (2009) estimated the area cleared and degraded each year between 1972 and 2002 using a forest change model. This model apportioned the total measured area deforested and degraded between 1972 and 2002 to individual years based on annual timber and oil-palm exports, population data, and El Niño occurrence and intensity (Shearman et al., 2009). We used the same model to apportion our best upper and lower estimates of total gross biomass lost through degradation and deforestation between 1972 and 2002 to each individual year over that period. We also report annual carbon loss by multiplying the annual biomass loss by 0.5.

3. Results

The average biomass of our unlogged forest measurements was 358 t/ha (SD = 108, $n = 22$). Logged forest biomass in the PSPs ranged from 98 to 286 t/ha, with the average of all plots being 161 t/ha (SD = 47, $n = 35$). Our best estimate of biomass stocks in PNG's rainforests in 2002 was 9541 Mt, equating to 4770 Mt of carbon. Our best estimate of unlogged rainforest biomass stocks was 9070 Mt, and our best estimate of logged forest biomass stocks was 471 Mt.

Across all (logged and unlogged) forest extent, our upper and lower estimates of total rainforest biomass stocks were 13% higher and lower respectively than our best estimate(Table 2). Comparison of our logged forest biomass stock estimates revealed that the upper estimate was 10% higher, and the lower estimate 10% lower than the best estimate. In unlogged forest, the upper estimate was 13% higher, and the lower estimate 13% lower than the best estimate.

The mean of the PNG measurements (358 t/ha) was significantly higher than the mean of the pan-tropical measurements (300 t/ha, $t = -2.48$, df = 22, $p < 0.05$). The majority of pan-tropical measurements came from the Amazon (Malhi et al., 2006; Brown and Lugo, 1982) and were centred around 26–27 °C (Fig. 1). However, when biomass measurements from locations with mean annual temperatures of less than 24 °C were excluded, the mean of the PNG measurements (386 t/ha) was still significantly higher ($t = -2.31$, df = 8, $p < 0.05$) than the mean biomass of the pan-tropical measurements (301 t/ha).

Table 2
Biomass and carbon (Mt) stored in PNG's rainforest 2002.

Estimate	All		Unlogged		Logged	
	Biomass (Mt)	Carbon (Mt)	Biomass (Mt)	Carbon (Mt)	Biomass (Mt)	Carbon (Mt)
Best	9541	4770	9070	4535	471	236
Lower	8283	4142	7859	3930	424	216
Upper	10798	5399	10280	5140	518	259

Our best estimate of total gross biomass and carbon loss between 1972 and 2002 (through both deforestation and degradation) were 2356 and 1178 Mt respectively. Upper and lower estimates of total gross carbon flux were 18% higher and lower respectively than the best estimate (Table 3), 10% resulting from estimation of biomass loss due to deforestation and the remaining 8% from estimation of biomass loss due to degradation.

By applying a forest change model based on timber exports, population increase, El Niño occurrence and frequency and oil-palm exports (Shearman et al., 2009), we estimated that annual carbon released through deforestation and degradation rose from 24 Mt in 1972 to 53 Mt in 2001, with logging (deforestation and degradation) accounting for 21% of total emissions in 1972 rising to 41% in 2001 (Fig. 2). Our upper and lower estimates of annual carbon flux 2001 were 18% higher and lower than our best estimate respectively.

4. Discussion

The total quantity of annual carbon emissions from land-use change in the tropics is uncertain, with estimates of annual carbon emissions ranging from 0.8 to 2.4 gigatons (Gt) (Fearnside and Laurance, 2004; Houghton et al., 2000; Schimel et al., 2001; Achard et al., 2002). Based on our best estimate of PNG's 2001 emissions from deforestation and degradation, PNG was responsible for between 2 and 7% of global tropical emissions. For a small and largely rural population, PNG's contribution to global tropical emissions from land-use change is striking.

Our finding that logging accounted for 41% of PNG's emissions from deforestation and degradation in 2001, rising from 21% in 1972, indicates that management of the forestry industry will necessarily be a priority if PNG is to participate in REDD. Further, our findings that annual forest emissions as determined from our forest change model (Fig. 2) have increased rapidly and substantially between 1972 and 2002 highlight the urgency of PNG reforming forestry practices. The increase in emissions between 1972 and 2002 is due to rapid increases in timber exports, population increase, and large forest fires, especially those associated with the 1997 El Niño event (Shearman et al., 2009).

Our best estimate of carbon stocks in tropical rainforest in 2002 (4770 Mt, Table 2) is within the range of the previously published estimates for PNG's forests, 4154–8037 Mt (Gibbs et al., 2007). However this previous estimate contains all forests whereas we have only examined rainforest. Our upper and lower estimate of 2002 carbon stocks indicates that PNG's rainforests contain 1–4% of global tropical forest carbon stocks as reported in Gibbs et al. (2007).

Our results suggest that while it is possible to generate a range of estimates for carbon storage (4142–5399 Mt, Table 2) and flux (966–1390 Mt between 1972 and 2002, Table 3) from a variety of source datasets, there remains a high degree of uncertainty regarding their actual value. Most of the uncertainty in our estimate of carbon stocks (Table 2) was associated with measurement of unlogged biomass, because the area of unlogged forest in 2002 (25,332,253 ha) was much greater than the area of logged forest (2,919,714 ha). However, uncertainty in our carbon flux estimates (Table 3, Fig. 2) was associated with measurement of unlogged forest biomass in addition to measurement of logged forest biomass and logging damage. This is because the area degraded accounted for 37% of the total area of forest change, whilst the area deforested accounted for 63%.

Table 3
Total biomass and carbon lost from PNG through deforestation and degradation 1972–2002.

Estimate	All loss		Deforestation		Degradation		All logging	
	Biomass (Mt)	Carbon (Mt)	Biomass (Mt)	Carbon (Mt)	Biomass (Mt)	Carbon (Mt)	Biomass (Mt)	Carbon (Mt)
Best	2356	1178	1781	891	574	287	892	446
Lower	1931	966	1544	772	388	194	663	332
Upper	2780	1390	2019	1010	760	380	1121	560

Fig. 2. PNG gross annual carbon flux from deforestation and degradation (Mt) 1972–2002. The solid line shows the best estimate, with the dashed lines above and below representing the upper and lower estimate respectively.

One of the primary problems in the estimation of biomass in PNG by applying the commonly used methodology of extrapolating field measurements of biomass across the landscape using forest mapping and environmental variables (Brown, 1997; Houghton et al., 2001; Malhi et al., 2006; Saatchi et al., 2007) is the lack of biomass measurements in unlogged forest. This methodology was originally based on the notion that tropical countries had spatially extensive forest plot inventories containing tree measurements which had been collected for the purpose of assessing timber harvesting potential (Brown, 1997). Unfortunately, the published inventories collected in PNG have focused on commercial species only (Hammermaster and Saunders, 1995). The ratio of commercial to non-commercial species varies greatly from plot to plot, and region to region (Hammermaster and Saunders, 1995) and cannot therefore be used to accurately estimate total forest biomass (Brown, 1997).

Our estimate of unlogged biomass could be improved by conducting more field measurements across a range of environmental conditions. Elsewhere in the tropics, spatial variation in forest biomass has been found to be related to a range of factors in addition to temperature, such as successional stage, rainfall, rainfall seasonality, soil and topographic variation (Saatchi et al., 2007; Asner et al., 2009; Brown and Lugo, 1982). Although we did not find a significant correlation between temperature and biomass, this may be because the effects of temperature on biomass interact with other environmental factors such as rainfall, topography or soil. It may be the case that the impact of temperature on biomass is important at temperatures below 10 °C (Fig. 1), above which other factors have a greater influence on variation in biomass stocks. Therefore, inclusion of additional variables in extrapolating unlogged biomass could improve our best estimate and reduce the variation of our upper and lower estimates around this best estimate. However such a multi-variable extrapolation could only reasonably be undertaken using a greater number of field estimates – 22 measurements is too small a sample size for multivariate analyses (Adcock, 1997). Nevertheless, our compilation of 22 biomass measurements and field inventories from ecological studies generated an order of magnitude more PNG-specific measurements than all other previous estimates of biomass in PNG (Achard et al., 2002; Houghton, 1999; Defries et al., 2007; Gibbs et al., 2007).

The fact that PNG-only biomass estimates were on average significantly higher than the non-PNG pan-tropical plots (Fig. 1) highlights the need for additional PNG biomass measurements, as it is not clear whether this is due to a genuine difference in forest biomass or bias in the PNG measurements. A possible explanation is that the PNG forest measurements we collated were collected largely for ecological or commercial forestry studies and may be biased towards accessible, high biomass sites, and hence may overestimate biomass in the broader forested region (Clark, 2007). However it should also be noted that PNG is a tectonically active landscape and has in general higher soil nutrient content and hence higher fertility than does much of the Amazon, from which most of the pan-tropical plots are derived (Laurance et al., 1999; Bleeker, 1983). Hence the higher biomass of the PNG plots may be genuine, and due in part to greater soil fertility. This uncertainty can only be overcome through the collection of more biomass estimates under a sampling regime designed to be representative of the range of overall forest carbon content, and one which covers a large area of forest (Fearnside and Laurance, 2004).

A further reason for uncertainty in our unlogged biomass estimates is the fact that several of these forest plots came from comparatively pure stands of *Nothofagus*. All forest types in PNG are not represented in our 22 measurements, and *Nothofagus* may well be over-represented which could result in a biasing of our unlogged biomass estimates. Additionally, the biomass measurements we have collated were estimated using a range of techniques and allometric equations. The lack of standard approach to biomass estimation is a large source of uncertainty in estimating biomass (Chave et al., 2005). The lack of a standard approach to measuring biomass may also be a reason why we found no correlation between temperature and biomass despite a strong temperature gradient existing in PNG. Again, these issues could only be overcome through conducting additional biomass measurements using a consistent technique, drawn from a sampling regime designed to measure biomass and to obtain a large enough sample size to classify the data according to dominant species composition.

These issues highlight the need for a national field survey collecting biomass data in unlogged forest. If PNG is to seriously participate in the REDD process in order to reduce carbon emissions from deforestation, then a large-scale program of forest biomass measurement in unlogged forest is necessarily a priority. This would also enable the relationship between forest biomass and ancillary information to be explored beyond the simple biomass–temperature relationship we examined in the present study, and hence improve the estimate of unlogged biomass. The fact that relationships between forest biomass and ancillary information fail to transfer well across tropical regions (Foody et al., 2003) further reinforces the necessity for new PNG measurements.

The utility of the 35 forest plot measurements in logged forest was limited for two main reasons. The first is that no measurement in these plots was conducted prior to logging, and hence we had to rely on our own estimate of unlogged forest biomass (described above) to estimate the amount of biomass that had been lost through logging. The PSP data were originally collected to determine the time necessary to regenerate commercially viable timber stocks (Cameron and Vigus, 1993), but the failure to measure pre-logging condition in each of the plots seriously limits the utility of this dataset for monitoring carbon stock regeneration. As the initial carbon stock is unknown, carbon loss and potential carbon stock is impossible to directly quantify. Thus although the PSP data in PNG is spatially extensive, its use is limited. PNG urgently needs to establish PSPs in forest where inventories are conducted prior to, as well as after, logging. A further limitation to the use of the PSP data is that each plot covers only a very small area of forest (1 ha) and therefore does not capture the inherent variability of forest biomass.

A further issue with our estimates of logged forest biomass is that we have allocated the same biomass to all logged forest regardless of the time since logging. After logging, the residual forest is vulnerable to further degradation or conversion to non-forest cover by burning, repeat logging, the incursion by shifting cultivators, or because the initial logging caused substantial damage to residual trees which progressively die after logging ceases (Holdsworth and Uhl, 1997; Lewis, 2006). This means that actual logged forest biomass may be less than our best estimate if initial logging was intensive, if further logging or subsequent fire has occurred, or if incursions by shifting cultivators were made after logging ceased. However, over centuries, in the absence of exogenous disturbance, logged forest may regenerate to pre-logging biomass levels. This means that in reality the biomass of logged forest may be more than our best estimate suggests if logged forest has been recovering.

There was also considerable uncertainty in our estimate of carbon flux, largely because we relied on our own estimates of unlogged and logged biomass and hence have included all the associated uncertainties outlined previously. Previous studies from other tropical regions have found that 20–80% of biomass was killed by logging-related degradation (Houghton, 1999). A recent logging damage study from western PNG found that approximately 30% of biomass was killed due to selective logging operations (Bryan et al., submitted). Our best estimate of gross biomass killed due to degradation is within this range as it equates to 55% of our best estimate of potential unlogged biomass. Although our best estimate seems reasonable, the considerable variation amongst our best, upper and lower estimates of biomass killed due to degradation could be reduced by conducting additional logging damage studies. As tropical logging is highly heterogeneous in intensity (Asner et al., 2005; Shearman et al., 2009), adequate estimation of associated biomass losses in PNG will require more studies from a range of different forest types and logging operations.

5. Conclusions

It is clear from our results that estimates of carbon stocks and carbon losses from PNG could be improved, and we have identified two areas of priority research which could allow this to occur. Firstly, the measurement of biomass in many more logged and unlogged forested locations across PNG needs to be conducted. This should be undertaken according to a consistent technique to measure biomass, and a randomized sampling regime to avoid uncertainty associated with selecting forest plots in accessible high biomass forest. This would also enable relationships between environmental variables and biomass in PNG to be better explored. Secondly, many more logging damage studies with pre-logging as well as post-logging biomass measurements need to be conducted in order to adequately measure carbon losses through logging. This would allow a more accurate estimate of carbon stocks which might be protected via avoided deforestation and forest regeneration schemes.

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