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Assessment of Aboveground Carbon in Primary and Selectively Harvested Tropical Forest in Papua New Guinea

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ABSTRACT

Papua New Guinea (PNG) has become the focus of climate change mitigation initiatives such as reducing emissions from deforestation and forest degradation, but defensible estimates of forest carbon are lacking. Here we present a methodology for estimating aboveground forest carbon, and apply it to a large Permanent Sample Plot system maintained by Papua New Guinea Forest Research Institute. We report the first estimates of forest carbon in lowland tropical forest in PNG. Average aboveground carbon in stems > 10 cm diam. for 115 selectively harvested 1-ha plots in lowland tropical forest was 66.3 ± 3.5 Mg C/ha (95% CI) while for 10 primary forest plots the average was 106.3 ± 16.2 Mg C/ha. We applied ratios based on field observations, in-country studies, and the literature to estimate unmeasured pools of aboveground carbon (stems < 10 cm diam., fine litter and coarse woody debris). Total aboveground carbon was estimated at 90.2 and 120.8 Mg C/ha in selectively harvested and primary lowland forest, respectively. Our estimate for primary tropical forest is lower than biome averages for tropical equatorial forest, and we hypothesize that frequent disturbances from fire, frost, landslides, and agriculture are limiting carbon stock development. The methodology and estimates presented here will assist the PNG government in its preparedness for mitigation initiatives, are of interest to communities that are seeking to participate in voluntary carbon markets, and will encourage transparency and consistency in the estimation of forest carbon.

Key words: biomass; deforestation; degradation; permanent plot; REDD; secondary; selective harvesting.

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Papua New Guinea (PNG), along with other rain forest nations, has become the focus of the climate change mitigation initiative reducing emissions from deforestation and forest degradation (REDD) in developing countries (UNFCCC 2006, 2009). Developing rain forest nations such as PNG face many challenges in reporting for the REDD initiative. Estimating forest carbon (C) pools in different forest strata such as primary and selectively harvested forest is an important precursor to REDD implementation (Gibbs *et al.* 2007, Kauffman *et al.* 2009). Here we quantify aboveground C stock in undisturbed (primary) and selectively harvested forest across a Permanent Sample Plot (PSP) network initiated and maintained by PNG Forest Research Institute (PNGFRI). Based on PSPs in selectively harvested lowland forest we can determine defensible provincial averages for carbon in aboveground biomass (AGB) that will assist the PNG government move toward a Tier 3 compliant greenhouse gas (GHG) inventory of forested land (IPCC 2006). Methods and results described here are also of interest to communities in PNG that are seeking to participate in voluntary carbon markets.

Secondary forest can be defined as forest that has been disturbed and is at some stage of regeneration, and has been estimated to comprise 40 percent of all tropical forest (Brown & Lugo 1990). Forests disturbed by selective harvesting can be grouped with other secondary forests (Makana & Thomas 2006) such as those disturbed by agriculture, which collectively represent a significant global C pool (*ca* 20%; Phillips *et al.* 1998) that has considerable potential for C sequestration into the future (Brown 1996, Fehse *et al.* 2002). Secondary tropical forest remains a poorly understood resource relative to primary forest (Sierra *et al.* 2007b, Kauffman *et al.* 2009). Many studies fail to adequately distinguish between primary and secondary forest (Houghton *et al.* 2001), and merge estimates of forest C over the two stratum. Consistent with this, selectively harvested forest in PNG is a large and poorly understood resource (Filer *et al.* 2009). A recent study suggested that the area of selectively harvested forest in PNG may be rapidly expanding (Shearman *et al.* 2009). Despite contentions concerning the actual rate of selective harvesting and forest degradation (Filer *et al.* 2009), it is generally agreed that if the current level of harvesting continues, remaining accessible commercial forest may be harvested in the next 15 yr (Filer *et al.* 2009, Shearman *et al.* 2009). Assessment of C stocks in this large and expanding resource is a priority for the inclusion of forest-related C dynamics in climate change mitigation initiatives.

Many previous studies of tropical forest C have been subject to methodological problems that have limited the reliability of the estimates (Clark *et al.* 2001b, Phillips *et al.* 2002). Several important problems have been identified: small plot sizes of < 1 ha (0.25 ha is common) limit the representativeness of measured forest and are likely to result in overestimates generated by larger trees being overrepresented (Brown & Lugo 1992). Lack of replication across forest stratum and in time and space again limit the representativeness of measured forest and will produce results skewed toward patches of forest with the highest biomass (Clark *et al.* 2001a,b; Phillips *et al.* 2002, 2004). These methodological problems are further

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complicated for tropical forests due to high spatial variability, structural and biological complexity, and complex temporal dynamics due to successional processes (Chambers *et al.* 2001). There is clearly a need for studies with large plots that sample widely across space in different forest strata, are subject to repeated measurement to capture temporal dynamics, and that more effectively deal with measurement error (Clark *et al.* 2001a,b; Phillips *et al.* 2004). The PSPs used in this study overcome many of these methodological issues, and provide a sound basis for the estimation of forest C; plots are large (1 ha), are replicated across forest types, and have been subject to several measurements through time.

Clark *et al.* (2001a) and Phillips *et al.* (2002) compile extensive dossiers of the measurement errors that may affect tropical forest census. The most significant source of error for tree census in tropical forests is associated with buttressing (Clark *et al.* 2001a, Phillips *et al.* 2002, Chave *et al.* 2003, Baker *et al.* 2004a). Buttressing is very common in rain forest trees, and becomes more prevalent as the trees get larger, with stem deformity often reaching several meters up the bole from the base. These deformations make accurate measurement of actual bole dimensions at breast height (1.3 m) almost impossible, and significant measurement errors can be introduced (Phillips *et al.* 2002). In PNG, when measurement above the buttress is impossible, it is acceptable practice to hold a measuring tape against the bole at breast height and visually estimate diameter (PNGFRI 1994). To avoid such estimates researchers recommend using ladders to access bole above the buttress (Phillips *et al.* 2002, Baker *et al.* 2004b), but this has rarely been done in PNG. In light of the potentially large measurement errors associated with buttressing we need a considered methodology for flagging and correcting erroneous measurements. Previous error correction methods include using interpolation (Chave *et al.* 2003, Lewis *et al.* 2009), stand-level (Baker *et al.* 2004a), or species-level averages (Rice *et al.* 2004). A considered methodology is required to avoid the potential for significant biases if erroneous records were simply removed from the data base as large buttressed trees contribute significantly to biomass estimates (Chave *et al.* 2003).

Another methodological issue is introduced when tree variables measured for timber inventory purposes are used to estimate biomass and C (Lindner & Karjalainen 2007). Two methods are commonly used: the first converts tree volumes to biomass using a biomass expansion factor (Segura 2005); the second uses previously developed allometric equations to estimate biomass per tree as a function of tree parameters such as tree diameter, tree height, and wood density (Brown *et al.* 1989, Clark *et al.* 2001a, Chave *et al.* 2003, Baker *et al.* 2004b). These allometric equations will have been derived from biomass harvesting studies (Brown *et al.* 1989, Chambers *et al.* 2001, Chave *et al.* 2001), and their application is dependent on the availability of equations for a similar forest, and also for similarly sized trees (Chave *et al.* 2005). Many allometric equations use only diameter to predict tree biomass, however, including wood density and height can improve the accuracy of tree level predictions (Chave *et al.* 2004, 2005), particularly considering the variation in tree architecture and wood density in tropical forests. Given the absence of allometrics for PNG we are forced to convert measured tree parameters to tree biomass using allometrics derived from other equatorial tropical forest. In doing this, it is important to include drivers of tree architecture and the physiological characteristics that determine C composition such as diameter, height, and wood density (Baker *et al.* 2004b, Chave *et al.* 2005).

The only previous estimate of forest C for PNG is the seminal work of Edwards and Grubb (Edwards 1977, Edwards & Grubb 1977) based on the destructive sampling of a single 0.24 ha plot in mid-montane forest (2500 m asl) in the Eastern Highlands. They estimated several C pools, aboveground live biomass (AGLB) 155 Mg C/ha, belowground live biomass (BGLB) 20 Mg C/ha, fine litter (FL) 3.8 Mg C/ha, and soil 600 Mg C/ha. A regional estimate of C in AGB is available for PNG: 39 Mg C/ha (FAO 2006, Marklund & Schöne 2006). This regional estimate, however, is far lower than the appropriate Intergovernmental Panel on Climate Change (IPCC) default for lowland tropical forest: 180 Mg C/ha (IPCC 2006). PNG is 5° south of the equator, therefore biome averages for tropical equatorial forest should also be considered: Gibbs and Brown (2007) 164 Mg C/ha and Lewis *et al.* (2009) 202 Mg C/ha. Given the dearth of in-country information and the divergence of regional and biome averages there is much opportunity for stakeholder confusion and flawed agreements which are likely to discredit REDD as an emerging conservation finance strategy. Sound information on forest C pools is required so PNG can participate in climate mitigation initiatives and to ensure transparency and consistency.

The objectives of this study were to: (1) develop a metho dology for estimating aboveground forest C based on PNG specific biometric models and the best available international models; (2) use it to quantify aboveground C pools in selectively harvested and primary forest based on the PSP system, and other locally collected information; and (3) provide national and provincial averages of aboveground C for application in climate mitigation initiatives.

METHODS

PNGFRI'S PSP SYSTEM.—Over the last 20 yr PNGFRI has established and remeasured over 135 PSPs across PNG (Fig. 1). A majority (114) of the PSPs were established in selectively harvested lowland forests. Here we stratify PSPs by elevation-zone based on the PNG vegetation classification of Hammermaster and Saunders (1995): lowland rain forest (0–1000 m asl), lower-montane (1000–2000 m asl), and mid-montane forest (2000–3000 m asl). Only a small number of plots were located in selectively harvested lower- (4) and mid-montane (2) forest. Primary forests, or areas where the effect of past disturbance is no longer apparent, are modestly represented; 11 plots in lowland forest and two plots in lower-montane. See Table 1 for the PSP sample size in each elevation-zone. Each PSP plot was established and measured using procedures adapted from Alder and Synnott (1992) which are documented in PNGFRI (1994). Plots are 1 ha in size and trees are recorded in 25 sub-plots of 20 × 20 m. In the first measurement the location, quadrat, diameter, height, and crown characteristics are recorded for all trees > 10 cm. In subsequent measurements only the diameter and status of trees are recorded. A full set of tree

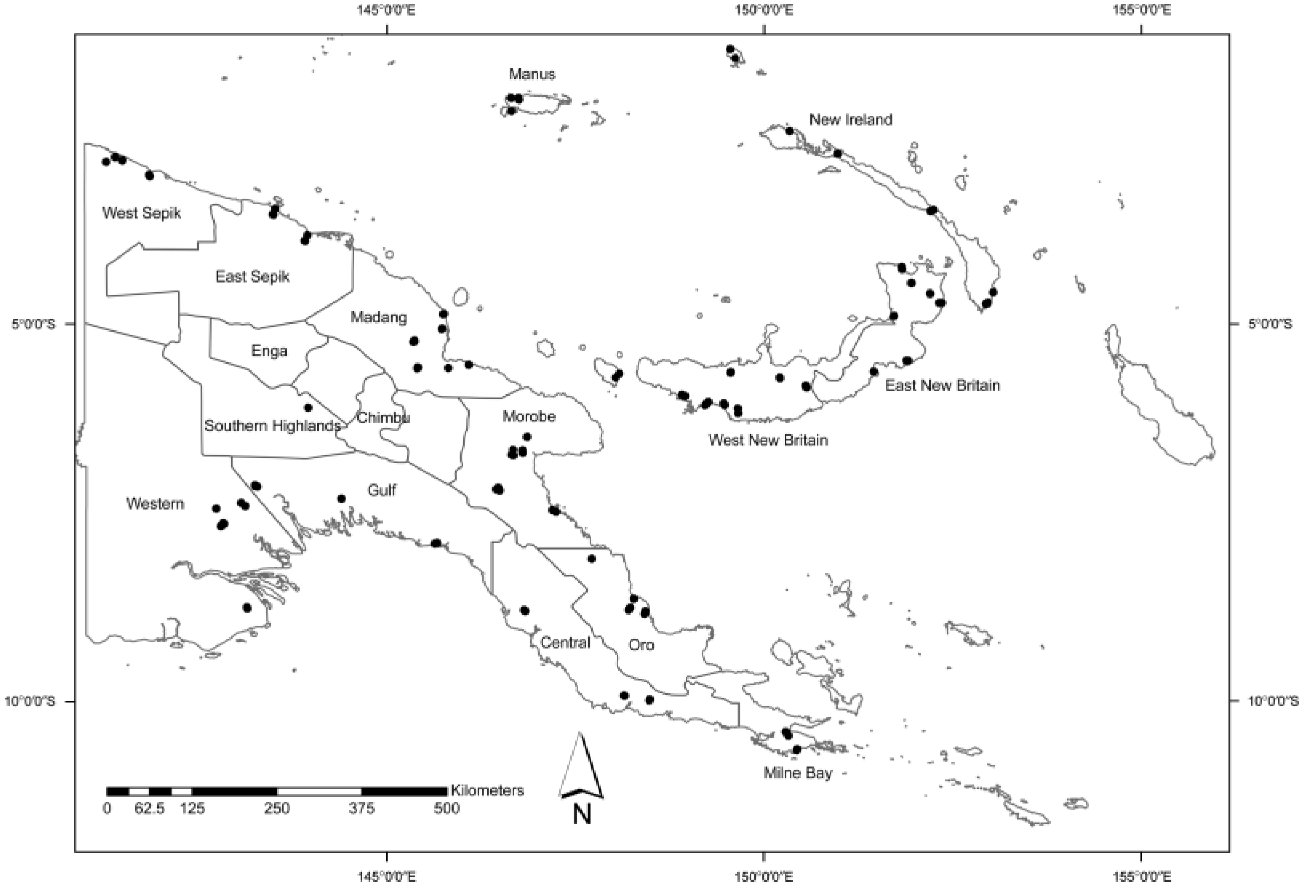

FIGURE 1. Location of PSPs (black points) in relation to the provincial boundaries of PNG.

attributes, however, is recorded for ingrowth. Plots in selectively harvested forest were randomly located in areas that had been subject to harvesting within the last 4 yr. The spatial distribution of PSPs across PNG is provided in Figure 1.

MEASUREMENT AND TRANSCRIPTION ERRORS.—Despite a well-developed and uniformly applied field procedure (Alder & Synnott 1992, PNGFRI 1994), problems often arise in large data bases due to measurement and transcription errors (Baker *et al.* 2004a), particularly those associated with buttressing (Clark *et al.* 2001a). To flag potential errors the distribution of diameter increments was examined, and those < -0.2, or > 2.6 cm/yr were flagged for investigation (Chave *et al.* 2003, Baker *et al.* 2004a). This represented *ca* 1 percent on each tail of the increment distribution. Several species (*Macaranga* spp., *Spondias* spp., *Hernandia* spp., *Palaquium* spp., *Melanolepis* spp., *Antiarus* spp., *Litsea* spp., *Trichospermum* spp., *Artocarpus* spp., *Sterculia* spp., *Trema* spp., *Elaeocarpus* spp., *Labula* spp., *Endospermum* spp., and *Octomeles* spp.), however, were found to have valid growth rates beyond 2.6 cm/yr. To account for this a new upper limit was used when the species-specific 95th percentile of the diameter increment distribution exceeded 2.6 cm/yr. Examination of diameters for flagged trees often revealed transcription errors, such as an extra zero, or a missing zero. These were corrected on a tree-by-tree basis. We developed a species-specific diameter growth model that can be used for error correction (Appendix S1). From the total of 153,900 tree records, 326 (0.2%) were obvious transcription errors that were manually corrected, and 3418 (2%) were erroneous measurements that were corrected using modeled diameter increment (Appendix S1). This methodology was applied to PSP data iteratively to smooth

TABLE 1. *Number of plots and number of measurements by forest type in the PNG Forest Research Institute Permanent Sample Plot system.*

Forest type	Plots	Measurements	Fire-affected measurements	Other disturbances
Secondary				
Lowland	115	394	24	15
Lower-montane	4	16	0	0
Mid-montane	2	12	0	0
Primary				
Lowland	11	21	1	2
Lower-montane	2	4	0	2
Mid-montane	0	0	0	0

erroneous measurements. The number of flagged increments declined to zero after four iterations, and the PSP dataset was clean and ready for analysis.

Several PSP plot measurements were affected by fires associated with the El Niño-Southern Oscillation (ENSO) drought event of 1997/1998 (Barr 1999) and these plot measurements were set aside (Table 1), as the high rates of tree mortality resulted in declines in forest C that skewed analysis of unaffected measurements. Other plot measurements were affected by anthropogenic disturbances such as garden establishment and were also excluded from the analysis (Table 1).

SPECIES-SPECIFIC HEIGHT–DIAMETER MODELS.—Biometric modeling of tree heights is required to generate AGB estimates for all trees on PSPs. Tree heights are only measured when PSPs are first established, and for new ingrowth (see Appendix S2 for further details on height–diameter models).

WOOD DENSITY.—Wood density information is required to generate AGB estimates for all trees on PSPs, and is available for many PNG timber species in Eddowes (1977). Available wood specific gravity (density at 0% moisture content) information from Eddowes (1977) was combined with the compilation for Asian rain forest (IPCC 2006). The range of wood densities was apparent; *Cananga odorata* had a density of 0.275 g/cm^3 while *Diospyros ferrea* had a density of 0.98 g/cm^3. Because wood density has a multiplicative effect on biomass and C, *D. ferrea* will contain three times as much woody biomass (and C) as a similarly sized *C. odorata*. For species with no wood density information, an average value of 0.477 across all species on PSPs was used (Brown 1997, Chave *et al.* 2003). This is similar, although marginally smaller than the average value of 0.54 for the 50-ha plot on Barro Colorado Island (Chave *et al.* 2003). This may be because the average of Chave *et al.* (2003) was based on primary tropical forest, whereas ours is dominated by selectively harvested forest with a higher representation of lower wood density pioneer species. Wood density for the 50 most common species on PSPs can be found in Table S1.

ESTIMATING ABOVEGROUND LIVING BIOMASS.—The first step in quantifying forest C is to estimate AGLB in standing trees. There has been much recent work on the development of allometric equations for estimating biomass for tropical forests from tree inventory information. Typically, they are models derived from destructively sampled trees and easily measured biometric variables such as diameter and height (Liddell *et al.* 2007). In an extensive study of allometric models for tropical forests, Chave *et al.* (2005) found the most important predictors of AGB were diameter, wood specific gravity, total height, and forest type (dry, moist, or wet). They developed a model (1) for wet tropical forests that we used to estimate AGLB for trees on PSPs:

$$\mathrm{AGLB}_i = 0.0776\left[\rho_i D_i^2 H_i\right]^{0.940}, \tag{1}$$

where D_i is the diameter in centimeters, H_i is the total height in meters, and ρ_i is the wood specific gravity in grams per cubic centimeter for tree *i*. The resulting AGLB_i is the total biomass of the stem, crown, and leaves for tree *i* in kilograms. Chave *et al.* (2005) found that locally, the error on the estimation of a tree's biomass was in the order of ± 5 percent. Average AGLB (and other tree statistics) for the 50 most common species on PSPs can be found in Table S1.

Total $\mathrm{AGLB}_{>10\,\mathrm{cm}}$ for each plot was quantified by summing tree level AGLB_i estimates for all *j* trees on the 1-ha plots as follows:

$$\mathrm{AGLB} = \sum_j \mathrm{AGBL}_i. \tag{2}$$

The C fraction of biomass will solely be reported in megagrams of C/ha (Mg C/ha) assuming that dry biomass is 50 percent C (Clark *et al.* 2001a, Houghton *et al.* 2001, Malhi *et al.* 2004). This is an acceptable approximation; however, the wood C fraction does exhibit some small variation across species and tree ages (Elias & Potvin 2003).

ESTIMATING TOTAL AGB.—Estimates of total AGB were derived from the measured component ($\mathrm{AGLB}_{>10\,\mathrm{cm}}$), previously established relationships, literature reviews, and field observations. Total AGB is the sum of $\mathrm{AGLB}_{>10\,\mathrm{cm}}$, AGLB in trees and other plants < 10 cm ($\mathrm{AGLB}_{<10\,\mathrm{cm}}$), and nonliving biomass (NLB):

$$\mathrm{AGB} = \mathrm{AGLB}_{>10\,\mathrm{cm}} + \mathrm{AGLB}_{<10\,\mathrm{cm}} + \mathrm{NLB}. \tag{3}$$

$\mathrm{AGLB}_{<10\,\mathrm{cm}}$ consists of small trees (< 10 cm), palms, shrubs, vines, and herbaceous plants. In undisturbed forest the biomass in this unmeasured component has been estimated to be 3–7 percent of the $\mathrm{AGLB}_{>10\,\mathrm{cm}}$ (Chave *et al.* 2003, Baker *et al.* 2004a). Edwards and Grubb (1977) found that $\mathrm{AGLB}_{<10\,\mathrm{cm}}$ constituted only 3 percent of total AGLB in primary mid-montane forest in PNG. In secondary or disturbed forest, however, this fraction may rise to as much as 20 percent depending on the degree of disturbance and the age of the secondary forest (Brown & Lugo 1990, Lugo & Brown 1992). Palms are often observed on PSPs, but are not included in tree inventories, and in some of the more heavily disturbed PSPs, small regrowth, shrubs, and herbaceous plants can be plentiful. Based on field observations, communications with measurement staff, and published literature (Edwards & Grubb 1977, Lugo & Brown 1992, Chave *et al.* 2003, Baker *et al.* 2004a) a factor of 10 percent of $\mathrm{AGLB}_{>10\,\mathrm{cm}}$ was used to estimate $\mathrm{AGLB}_{<10\,\mathrm{cm}}$ for selectively harvested forest, and 5 percent for undisturbed forest.

NLB consists of necromass in coarse woody debris (CWD) consisting of standing dead and fallen trees, and FL consisting of remaining dead plant material (fruits, leaves, flowers, and small branches) on the forest floor. FL in tropical forests has been estimated to be 5 percent of $\mathrm{AGLB}_{>10\,\mathrm{cm}}$ (Brown & Lugo 1982), and the IPCC (2006) default for FL is 1.05 Mg C/ha. Edwards (1977) sampled litter from a primary mid-montane forest in PNG and found an average quantity of 3.8 Mg C/ha. Preliminary information collected by PNGFRI indicated that litter depth was shallow in lowland selectively harvested PSPs with an average depth of 1.5 cm across 188 samples. Litter depth was increased in selectively harvested montane forest with an average of 12 cm across 48 samples. Explanation of this result can be found in the slower litter decay rates in montane forest as compared to lowland forest due to lower average temperatures (Edwards 1977, Rogers 2002). A much greater litter depth was observed for undisturbed montane forest (36 cm across 36 samples). Following these trends we estimate that the FL component is 1 and 2.5 percent of $AGLB_{>10\,cm}$ in lowland and montane selectively harvested forest, respectively, and 2.5 and 4 percent in lowland and montane primary forest, respectively. Application of these ratios results in similar magnitudes of FL as IPCC defaults and as previously observed in PNG; 0.7–1.5 and 2.6–5.6 Mg C/ha in selectively harvested and primary forest, respectively.

CWD is potentially a large C pool, particularly in disturbed forest, and may constitute 10–40 percent of AGB (Uhl & Kauffman 1990). Palace *et al.* (2007) found that selectively harvested forest in the Amazon had 50 percent more CWD than undisturbed forest. Based on field observations, we estimate CWD to be 25 percent of the $AGLB_{>10\,cm}$ in selectively harvested forest and 10 percent of the $AGLB_{>10\,cm}$ in undisturbed forest. This ratio results in average CWD values of 16.6 and 10.3 Mg C/ha in selectively harvested and primary lowland forests, respectively. These values are similar to the IPCC (2006) default value for CWD of 18.2 Mg C/ha as applied in other studies (*e.g.*, Herold *et al.* 2008). Final percentage estimates of FL, CWD, and NLB are detailed in Table 2. NLB values of 12.9–19.7 as estimated in Table 3 are consistent with previous estimates of 10–20 percent of AGB (Houghton *et al.* 2001, Achard *et al.* 2002). Importantly, the ratios result in relatively consistent additions to $AGLB_{>10\,cm}$ across forest stratum, and therefore do not add unnecessary noise to the original measured component. Total AGB can be estimated using equation (3).

AVERAGING ACROSS PSPs.—Following the estimation of $AGLB_{>10\,cm}$ and AGB for each PSP remeasurement, the following methodology was used to generate stratum, provincial, and national averages. PSPs in selectively harvested and undisturbed forest were analyzed separately (Table 1). Averages for $AGLB_{>10\,cm}$ and AGB were initially averaged across the remeasurements of each PSP. The average value for each PSP was then used in stratum, elevation-zone, provincial, and national averages. This approach assumes that PSP remeasurements are a representative sample of the various growth stages of selectively harvested forest. It is statistically sound as each PSP is represented in final averages by a single observation, thus excluding the statistical problems associated with temporal autocorrelation within PSP remeasurements (West *et al.* 1986, Fox *et al.* 2001).

TABLE 2. *Unmeasured AGB components as percentages of $AGLB_{>10\,cm}$ (units $\%AGLB_{>10\,cm}$).*

	Secondary			Primary		
	Lowland	Lower-montane	Mid-montane	Lowland	Lower-montane	Mid-montane
$AGLB_{<10\,cm}$	10	10	10	5	5	5
FL	1	2.5	2.5	2.5	4	4
CWD	25	25	25	10	10	10

DETERMINATION OF REQUIRED SAMPLE SIZE AND ERROR BUDGET.—This study is effectively a pilot survey of forest C stock in PNG. Using a standard formula (Philip 1994) we can determine the precision of the estimate of the mean values and the number of plots required to improve precision to desired levels as follows:

$$n = \frac{CV^2 t^2}{E^2}, \qquad (4)$$

where n is the number of samples, CV is the coefficient of variation, t is the Student's t value for a 95% CI at the specified degrees of freedom, and E is the required precision, *e.g.*, within 5 or 10 percent of the true mean.

RESULTS

Average $AGLB_{>10\,cm}$ for 115 PSPs in selectively harvested lowland tropical forest measured between 1992 and 2008 was 66.3 Mg C/ha (SD 18.8). Average $AGLB_{>10\,cm}$ for ten PSPs in primary lowland forest was 106.3 Mg C/ha (SD 22.7; Table 3). Selectively harvested $AGLB_{>10\,cm}$ was relatively consistent across the forest strata (58.8–66.3 Mg C/ha; Table 3). 95% CIs on these averages were 66.3 ± 3.5 Mg C/ha in selectively harvested lowland forest and 106.3 ± 16.2 in primary lowland forest. Averages were within 5.2 and 15.3 percent of the true mean (95% CI) for selectively harvested and primary lowland forest, respectively. Based on the observed variance, a total of 126 and 93 PSPs are required for 5 percent accuracy at a 95% CI for selectively harvested and primary forest, respectively. Therefore an additional 11 and 83 PSPs are required to achieve this level of precision. For 10 percent accuracy (95% CI), 22 and 15 PSPs are required in selectively harvested and primary forest.

TABLE 3. *Estimates of the mean carbon stock in different pools in different forest types in Papua New Guinea. Quantities for all components are Mg C/ha (± SD).*

	Secondary			Primary	
Forest C component	Lowland	Lower-montane	Mid-montane	Lowland	Lower-montane
$AGLB_{>10\,cm}$	66.3 (18.8)	58.8 (9.8)	61.3 (19.6)	106.3 (22.7)	141.1 (25.6)
$AGLB_{<10\,cm}$	6.7	5.8	6.1	5.1	7.1
Total AGLB	73.0	64.6	67.4	111.4	148.2
FL	0.7	1.5	1.5	2.6	5.6
CWD	16.6	14.7	15.3	10.3	14.1
Total NLB	17.3	16.2	16.8	12.9	19.7
Total AGB	90.2 (25.6)	80.9 (13.5)	84.3 (26.9)	120.8 (22.5)	167.9 (30.4)
Sample size	115	3	2	10	2

The estimate of the mean C stock in AGB was 90.2 Mg C/ha (SD 25.6) for selectively harvested and 120.8 Mg C/ha (SD 22.5) for primary forest.

Average $AGLB_{>10\,cm}$ in selectively harvested lowland forest ranged from 50–55 Mg C/ha in Oro, Manus, and Central Provinces to 72–86 Mg C/ha West Sepik, West New Britain, Western, and Morobe Provinces (Table 4). More confidence can be placed in estimates for provinces with reasonably high plot numbers such as Morobe, New Ireland, East New Britain, West New Britain, and Madang.

DISCUSSION

Forest timber inventory data have been widely used to estimate forest C stocks. It has the advantage of being an extensive and generally representative sample of the forest, often at a national level (Brown & Gaston 1995, Phillips *et al.* 1998, Baker *et al.* 2004a, Lindner & Karjalainen 2007). This is the case with PNGFRI's PSP network. However, timber inventory data do have important shortcomings in providing estimates of forest C stock; the locations of plots may be biased toward productive forest that contains (or did contain) sufficient merchantable timber to justify a harvest; measured trees are generally restricted to merchantable species > 10 cm diameter at breast height (dbh); other forest C pools such as understorey, underground, and necromass are not accounted for (Chave *et al.* 2003). Beyond these shortcomings, timber inventory data have been extensively used for studying forest C (Baker *et al.* 2004a), and are a practical and sufficiently accurate method for estimating the C balance of tropical forests (Chave *et al.* 2003). The seminal works of Phillips and Gentry (1994), Phillips *et al.* (1998), and Lewis *et al.* (2009), which detected increased turnover rates and increasing biomass in primary Amazonian forest (although contentions exist; Clark *et al.* 2001a, Wright 2005), were also based on forest timber inventory data.

TABLE 4. *Results for average $AGLB_{>10\,cm}$ and AGB ($\pm$ SD) by Province for selectively harvested lowland tropical forest.*

Province	$AGLB_{>10\,cm}$	95% CI	Sample	AGB
Central Province	54.6 (12)	10	8	74.3
East New Britain	65.9 (27)	20	15	89.7
East Sepik	67.9 (17)	15	6	92.4
Gulf Province	61.9 (18)	16	9	84.1
Madang Province	57.3 (16)	17	10	77.9
Manus Province	54.1 (25)	46	4	73.6
Milne Bay Province	70.1 (15)	15	4	95.4
Morobe Province	73.6 (14)	10	9	100.0
New Ireland	69.4 (20)	14	12	94.4
Oro Province	50.4 (12)	10	8	68.5
West New Britain	72.9 (14)	9	16	99.1
West Sepik	72.9 (13)	12	8	99.2
Western Province	86.1 (10)	7	6	117.1
Overall	66.3 (18.8)		114	90.2 (25.6)

The PSP data base has provided a strong basis for estimating $AGLB_{>10\,cm}$. However, we still relied on a general allometric equation developed by Chave *et al.* (2005). Despite Chave *et al.* (2005) incorporating AGLB data from PNG (Edwards & Grubb 1977), we recommend further investigation of the suitability of these models within PNG, and an investment in the development of localized allometrics. Destructive sampling of two to three large trees may be all that is required to check and validate estimates from existing allometric equations (Gibbs *et al.* 2007). Beyond $AGLB_{>10\,cm}$, we were forced to use ratios to estimate unmeasured aboveground pools ($AGLB_{<10\,cm}$, FL, and CWD). Ratios were based on field observations, in-country studies, and the literature. Although this is permissible for national-level reporting (IPCC 2006, Marklund & Schöne 2006, Herold *et al.* 2008), the measurement of these missing aboveground pools is desirable to validate ratios and to consolidate estimates of AGB. Uncertainty associated with the application of ratios for unmeasured C pools results in errors that propagate through to final estimates (Chave *et al.* 2004).

PSP plots are often located in proximity to roads or villages, which has implications for anthropogenic disturbances from gardening and cultural burning through the census period. This may have implications for undisturbed PSPs, as it is possible that they may have been subject to some degree of previous disturbance. This may explain why C in undisturbed AGB (120.8 and 167.9 Mg C/ha in lowland and lower-montane forest) is lower than biome averages for tropical equatorial forest (Gibbs & Brown 2007: 164 Mg C/ha; IPCC 2006: 180 Mg C/ha; Lewis *et al.* 2009: 202 Mg C/ha). Our estimates, however, are far larger than the regional estimate of Marklund and Schöne (2006) of 39 Mg C/ha. The estimate of Marklund and Schöne (2006) attributes PNG forests to the Oceania region which has lesser forest biomass than SE Asia (Herold *et al.* 2008). Further, the estimate of Marklund and Schöne (2006) is based on the PNG country report (FAO 2005) including AGB above a 50-cm diameter threshold. Our estimate for lower-montane forest (167.9 Mg C/ha) is similar to the only previous estimate for PNG: Edwards and Grubb (1977) AGB of 155 Mg C/ha in mid-montane rain forest (2500 m asl).

An interesting point of discussion is the lower aboveground C in PNG tropical forest compared to the highly productive *dipterocarp* forests of SE Asia (Yamakura *et al.* 1986: 243 Mg C/ha in East Kalimantan; Aiba & Kitayama 1999: 256 MgC/ha in Sabah; Yamakura *et al.* 1996: 260 Mg C/ha in Sarawak). We can only speculate on reasons for this. PNG is susceptible to the ENSO which has cyclically induced drought in 1972, 1982, 1988, and 1998 (Brown & Powell 1974, Johns 1989, Barr 1999). These droughts have caused large-scale rain forest fires in lowland areas (Johns 1989) and severe frosts in montane forests (Allen 1989, Waddell 1989). PSPs affected by the 1998 ENSO, and the fires they induced, indicated dramatically increased mortality of up to 25 percent of basal area (C. Yosi, pers. comm.). Extrapolating this trend to cyclically observed ENSO events may provide a hypothesis for lower observed AGB in PNG. Indeed, Johns (1986, 1989) suggests that the frequency of ENSO-related droughts in PNG should prompt a reevaluation of both the age and stability of PNG's rain forest ecosystems. Beyond ENSO-induced drought, fire, and frost, the topography and heavy rainfall result in frequent large-scale landslides. Another important disturbance to PNG's rain forest ecosystems is agriculture; it has been practiced in PNG for 10,000 yr with stone tools and burning used to clear trees for garden establishment in shifting cultivation (Bourke 2009). We hypothesize that the cumulative influence of drought, fires, frosts, landslides, and agriculture will result in a dynamic mosaic of forest at different stages of succession. This mosaic will on average have lower aboveground C compared to tropical forests with less frequent disturbances.

The accuracy and representativeness of aboveground C estimates for undisturbed forest in this study are compromised by the small sample size. Data for this forest class need to be increased for effective analysis for forest C dynamics at a national scale. Our analysis of the variability in current primary aboveground forest C suggests that an additional 83 (total sample of 93) PSPs will be required in this stratum to achieve an estimate of total forest C at the national scale with ± 5 percent accuracy at a 95% CI. More plots will be required to provide precise estimates at a sub-national or local scale.

Differences in average $AGLB_{>10\,cm}$ among provinces for selectively harvested forest reflect differences in forest characteristics, productivity, and the intensity of selective harvesting. Provinces such as Oro and Central are dryer (McAlpine *et al.* 1983) and have generally less productive forests (Bellamy & McAlpine 1995) resulting in lower biomass estimates ($AGLB_{>10\,cm}$ 50–55 Mg C/ha). The forests of Manus Province are dominated by a single species (*Calophyllum*), which is targeted in selective harvesting (R. Johns, pers. comm.) resulting in a secondary forest with lower biomass (54 Mg C/ha). Provinces with higher observed aboveground C in selectively harvested forest (West Sepik, West New Britain, Morobe, and Milne Bay Provinces; 70–75 Mg C/ha) are generally more productive with higher rainfall. Western Province consists of alluvial plains with high annual rainfall (up to 6000 mm; McAlpine *et al.* 1983) and large continuous tracts of lowland tropical forest. These productive environs result in the highest observed AGLB in selectively harvested forest (86 Mg C/ha). The aboveground C in selectively harvested forest will be related to the resilience of the forest to disturbance. Future work should examine aboveground C dynamics in context of the resilience of different forest types to disturbance; intuitively, relationships should exist between forest recovery, substrate, climate, and composition.

Average selectively harvested AGB was 90.2 Mg C/ha in lowland forests; this is higher than secondary forest resulting from other land uses such as shifting agriculture (Sierra *et al.* 2007a: AGB 21 Mg C/ha) and more intensive selective harvesting practices in other regions (Pinard & Putz 1996: AGB 68 Mg C/ha). This may be because selective harvesting as practiced in PNG (targeting high-value species above a 50 cm diameter limit) has a lesser impact on forest C. Despite intentions of randomly selecting forest for census, however, the PSP network is susceptible to some plot selection bias; plots may have been positioned in better-stocked areas to justify the effort of access and measurement. Heavily degraded areas or areas with no potential for future timber production may have been avoided. However, the relatively large plot size of 1 ha overcomes some of these concerns.

Here we have estimated the aboveground component of forest C, however, it is likely that the belowground component is larger (Edwards & Grubb 1977, Hughes *et al.* 1999). During 2007, PNGFRI commenced a soil C sampling program for PSP plots. This preliminary work for 188 samples has indicated that for lowland selectively harvested PSPs the average soil C pool to a depth of 30 cm was 53 Mg C/ha. In lower- and mid-montane selectively harvested PSPs 48 samples revealed that the soil C pool was 113 Mg C/ha. Thirty-six samples in lower-montane undisturbed forest indicated a soil C pool of 103 Mg C/ha. This supports the previous finding that disturbances such as tropical selective harvesting have minimal influence on the soil C pool (IPCC 2006).

BGLB can be estimated from AGLB using established ratios (Herold *et al.* 2008). Estimated ratios for tropical forests are 0.37 for lowland tropical forests (Fittkau & Klinge 1973 cited by IPCC 2006) and 0.27 for tropical mountain systems (Singh *et al.* 1994 cited by IPCC 2006). These ratios for BLGB can be applied to PSPs, and the measured soil C fraction can be added to provide a tentative estimate of total forest C; 158, 200, and 205 Mg C/ha in selectively harvested lowland, lower-montane, and mid-montane forest, and 210 and 315 Mg C/ha in primary lowland and lower-montane forest, respectively. The veracity of these estimates, however, is dependent on limited field measurements and the use of a single ratio, both of which are compromised by the large spatial variation associated with belowground C pools (Wright *et al.* 1997, Klironomos *et al.* 1999). Further work is required to measure and estimate the soil C and BLGB components of forest C to more accurately estimate their contribution to forest C in PNG.

Here we have reported information on aboveground forest C pools in PNG; an important precursor to REDD implementation and of interest to communities within PNG that are hoping to participate in voluntary carbon markets. It is the change in forest C pools over time and consequent emissions of carbon dioxide to, or removals from (uptake of C in living biomass) the atmosphere due to different land uses, land use changes, and forestry (LULUCF) that is important for REDD implementation (Gibbs *et al.* 2007). The PSP data base provides a sound basis for estimating C dynamics associated with LULUCF, and in future work we hope to quantify C dynamics in secondary and primary forest in PNG, and elucidate changes in C pools due to selective harvesting.

In conclusion, this study provided the first comprehensive assessment of aboveground C stocks for tropical native forests in PNG. We also provided methods that can be used for estimating forest C from other forest inventory data, inclusive of an error correction methodology and allometric relationships between diameter and height that are important in improving the accuracy of C assessments in tropical forests. These results are an important contribution to policy discussions on the future management of PNG forests and the development of mechanisms for reducing greenhouse emissions from tropical forests. We hope that methods and results contained herein will encourage transparency and consistency in the estimation of forest C with PNG.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

TABLE S1. *Average statistics for the 50 most common species on PSPs.*

FIGURE S1. Fitted Box–Lucas diameter–diameter increment model for example species.

FIGURE S2. Fitted hyperbolic height–diameter model for example species.

APPENDIX S1. Methodology for species-specific increment model for error correction.

APPENDIX S2. Methodology for species-specific height–diameter models.

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