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Comparing above-ground biomass among forest types in the Wet Tropics: Small stems and plantation types matter in carbon accounting

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A B S T R A C T

Revenue from carbon credits from rainforest stands could encourage reforestation for biodiversity conservation on private land in north-eastern Queensland, Australia. Current models and allometrics for estimating carbon, however, are not calibrated against sites in the region and underestimate carbon stocks. We assess the accuracy of the two accepted methods to estimate carbon stocks in Australian rainforests: FullCAM and the Keith et al. (2000) allometric. We also assess the effect of FullCAM's discounting of small stems (2.5–10 cm) to carbon stocks, and compare the carbon benefits of the three reforestation methods in the region to identify planting configurations with the best carbon sequestration potential. We sampled 27 rainforest stands in north-eastern Queensland. Using these data we calculated above-ground biomass (AGB) using the Keith allometric and derived the above-ground carbon (AGC). We compared our estimates across three reforestation methods with the FullCAM modelled estimates for the same sites, and with estimates derived from two global rainforest allometrics (Brown, 1997; Chave et al., 2005). The Keith allometric estimated that planted forests yielded on average 20 Mg of tradable carbon ha^{-1} y^{-1} (i.e. CO_2-equivalent), with no differences between plantation forests and environmental plantings, although the former had more large diameter stems. Small stems (<10 cm) accounted for 15.1% of AGB in plantings <20 years old. However, even excluding these, the estimates using the Keith allometric were 19.5% greater than those of FullCAM; the Chave allometric 40.4% greater; and the Brown allometric 54.9% greater. More thorough forest mensuration using actual tree volumes and densities is required to determine a biomass allometric function for rainforests in the region. Until then, we recommend the Chave allometric function. It provides intermediate values, is based on the widest range of tropical trees and has been shown to be accurate away from the sites used for its development. This study demonstrates the inadequacy of current methods for estimating carbon stocks in rainforest plantings in north-eastern Queensland. A tailored allometric and the re-parameterisation of FullCAM is needed to reflect both the region's environmental characteristics and the vegetation structure of young reforestation stands. Current estimates deprive landholders of financial incentives and underestimate the national greenhouse gas benefits of tree planting in the Wet Tropics.

1. Introduction

Vegetation clearance has been the most significant threat to rainforests in the Wet Tropics bioregion of northeast Queensland, Australia. Over the last 100 years, over half of the 640,000 ha of forest on freehold land has been cleared, and clearing has continued over the last two decades, averaging 1661 ha cleared per year (Department of Environment and Resource Management, 2009). Over the same period, many landholders in the region have also replanted forests and encouraged regrowth for biodiversity conservation. Regrowth and replanted forests now make up about one third of the 350,000 ha of rainforest and wet sclerophyll forest currently growing on freehold land in the region. Replanted rainforests have considerable ecological and conservation value (Laurance, 1990, 1991, 1994; Harrington et al., 1997; Westcott et al., 2005; Dennis and Westcott, 2006). However, as they are not protected from clearing under the Queensland *Vegetation Management Act 1999* (which protects remnant and some

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high-value regrowth forest), the value they provide to biodiversity has no long-term security. This situation could be improved through revenue earned from carbon credits that is conditional on plantings being maintained into the future, as is the case under the emissions trading scheme proposed by Australian government (Carbon Farming Initiative, http://www.climatechange.gov.au/government/initiatives/carbon-farming-initative.aspx accessed 30th August, 2011). This scheme allows landowners to sell carbon sequestered in forest stands to industry and government to offset some of their greenhouse gas emissions.

To begin carbon trading, landholders need reliable estimates of the carbon sequestered in their forest stands. The Carbon Farming Initiative requires this be done using the National Carbon Accounting System (NCAS; Department of the Environment and Heritage, 2005), which uses FullCAM (full carbon accounting model) to model the sequestered carbon (Research Edition 3.13.8, Richards and Evans, 2000b). FullCAM is an integrated model that incorporates subordinate models for estimating biomass and carbon stocks. These include several large-scale flux models, and a combination of general forest growth tables, climate and environmental variables, a forest productivity index and a version of the 3-PG model of forest productivity (Landsberg and Waring, 1997; Australian Greenhouse Office, 2000; Kesteven et al., 2004). Users of FullCAM enter the location of the forest stand, and use descriptors of forest types included in FullCAM, including the type and year of planting and any treatments applied. One of the models within FullCAM, CAMFor (carbon accounting model for forests), uses a process model to predict above-ground biomass (AGB) and above ground carbon biomass AGC ($Mg\,C\,ha^{-1}$) based on: (1) the relationship between tree volume and age of the tree/stand; assumed or modelled maximum growth rate, maximum AGB; a maximum AGB multiplier; a tree yield multiplier; and age of maximum growth rate (Waterworth et al., 2007); (2) environmental variables that are assumed to be specific to a location (soil type, rainfall, temperature, solar radiation, type of agricultural and forest system, plantation types and ages, and estimated maximum AGB) (Australian Greenhouse Office, 2000; Richards and Evans, 2000a; Department of Climate Change and Energy Efficiency, 2010); and (3) a national, variable-scale grid (25 m to 1 km pixel) map of net primary production (Waterworth et al., 2007; Waterworth and Richards, 2008); and wood density characteristics. The formula and parameters used in CAMFor are based on a large range of forest data (Waterworth et al., 2007; Waterworth and Richards, 2008), but these are mostly from non-tropical areas and none are from the Wet Tropics. Consequently FullCAM has been shown to have variable accuracy in predicting AGB for sites of known value, particularly in the Wet Tropics (Kesteven et al., 2004). Moreover, neither the exact combination of formulae used to estimate AGB, nor the parameters applied at specific locations are completely apparent.

As part of the development of NCAS, a number of allometric relationships were also developed for estimating AGB, which are also in use. These allometrics, are not used in FullCAM calculations, and we have found that they produce estimates different from the modelled estimates from FullCAM. Among these allometrics, one developed by Keith et al. (2000) – hereafter referred to as the Keith allometric – is the only allometric function within the NCAS publications for estimating AGB of rainforests. This is despite the fact that the sites from which it was derived do not include Australian Wet Tropical rainforests. Lack of data from the Wet Tropics means that this allometric also has the potential to yield inaccurate results for the Wet Tropics.

In this study, we compare estimates of AGB for 27 rainforest sites in the Wet Tropics using the Keith allometric with those produced from two allometrics developed for moist tropical forests (Brown, 1997; Chave et al., 2005), as well as with estimates from FullCAM. We also assess the effect of FullCAM's discounting of small stems (dbh = 2.5–10 cm) on estimates of carbon stocks. We compare the carbon stocks achieved by the reforestation methods commonly used in the Wet Tropics to identify planting configurations with the best carbon sequestration potential. For the latter we examine whether the rates of carbon sequestered by widely spaced eucalypt and/or mixed species plantations differ from those of environmental plantings with close spacings (Keenan et al., 2005; Erskine et al., 2006; Kanowski and Catterall, 2010).

2. Methods

2.1. Sample sites

We sampled 25 forest plantings in the Wet Tropics, within 40 km north and south and 20 km east and west of 17.3° S, 145.6° E on the Atherton Tablelands. We also sampled one remnant rainforest site, and one regrowth rainforest site for comparison. The sites ranged in elevation from 600 m to 1000 m ASL. Mean annual rainfall is high, ranging from over 3000 mm in the east, to ~1200 mm in the western and northern sites, with peak rainfall months from November to March. Temperature ranges from a mean annual minimum of 15.6 °C to a mean maximum of 25.3 °C. Soils are derived from basaltic, granitic and metamorphic rocks, predominantly ferrosols with some dermosols. The original vegetation at all sites was rainforest, but most sites now contain only fragmented forest remnants.

Planted sites were classified according to type of planting, tree species composition and date of planting or start of regrowth (known or surmised; Table 1). Three planting types are commonly used for reforestation in the Wet Tropics: (1) plantations comprising mixed rainforest species (CRRP-mixed), and (2) eucalypt (CRRP-euc) plantations that are part of the Community Rainforest Revegetation Project, both having wide spacing between trees and hence referred to here as forestry plantings; and (3) environmental plantings comprising native rainforest species that were established by community groups and individuals. These tend to be more closely spaced and densely stocked. The remnant site, in Regional Ecosystem type 7.8.4 complex semi-evergreen notophyll vine forest (Queensland Herbarium, 2009), was last logged selectively over 50 years ago. The regrowth site, in Regional Ecosystem 7.12.16 simple to complex notophyll vine forest (Queensland Herbarium, 2009), began regenerating in about 1990.

Sampled stands varied in size from ~0.3 ha to 113 ha. Three plots were established in the regrowth site; two plots in the remnant rainforest site and in each of 23 of the planted stands, and one plot each in two small planted stands (making a total of 53 plots). Locations of plots were pre-selected from aerial photographs and satellite images to ensure plots were representative and avoided creek lines.

2.2. Tree measurement plot method

We used a modified transect method for recording tree locations within a 0.05 ha (50 × 10 m) plot (Stohlgren et al., 1995; Back et al., 1997; Back et al., 1999; Burrows et al., 2000; Burrows et al., 2002; Crowley et al., 2009), that ensures both accuracy and repeatability, and is suited to estimating high stem densities in rainforest patches on steep slopes. Sampling was conducted about the central line (x-axis) of each plot, which was oriented along a compass bearing (Fig. 1). The x and y coordinates of trees relative to this line were accurately recorded, along with stem size (diameter at breast height – dbh), measured to the nearest mm using a dbh tape. Trees were allocated to one of three size classes (large: >20 cm; medium: 10–20 cm; or small: 2.5–10 cm). While a

Table 1
Characteristics of the types of forest plantings in the Wet Tropics and investigated in this study.

Type of planting	Environmental plantings		CRRP-euc[a]		CRRP-mixed[a]		
No. of stands (plots)	15 (30)		3 (5)		7 (13)		
Planting periods	1990–2005		1992–96		1992–1996		
Stem spacing	1–2 m		3–4 m		3–4 m		
Stocking rate (stems ha^{-1})	>3000		~1000		~1000		
	Main families [b]	Main genera	Family and species	Wood density (kg m^{-3})	Family	Species	Wood density (kg m^{-3})
			Myrtaceae – (15 *Eucalyptus* spp.)				
	Elaeocarpaceae	*Elaeocarpus, Sloanea*	*Eucalyptus grandis* (34%)	597	Araucariaceae	*Araucaria cunninghamii* (29%)	442
	Euphorbiaceae	*Mallotus, Homalanthus*	*Eucalyptus cloeziana* (20%)	811	Araucariaceae	*Agathis robusta* (17%)	400
	Lauraceae	*Cryptocarya, Endiandra, Litsea, Neolitsea*	*Eucalyptus resinifera* (18%)	800	Rutaceae	*Flindersia brayleyana* (11%)	442
	Moraceae	*Ficus*	*Eucalyptus microcorys* (11%)	811	Elaeocarpaceae	*Elaeocarpus angustifolius* (9%)	410
	Myrtaceae	*Rhodamnia, Rhodomyrtus, Syzygium, Xanthostemon*	*Eucalyptus pellita* (8%)	811	Meliaceae	*Cedrela odorata* (4%)	350
	Proteaceae	*Alloxylon, Athertonia, Cardwellia, Darlingia, Helicia, Opisthiolepis, Stenocarpus*	*Eucalyptus pilularis* (8%)	699	Fabaceae	*Castanospermum australe* (4%)	583
	Rutaceae	*Flindersia, Melicope*	*Eucalyptus citriodora* (3%)	800	Anacardiaceae	*Blepharocarya involucrigera* (4%)	453
	Sapindaceae	*Castanospora, Cupaniopsis, Diploglottis, Guoia, Mischocarpus*	*Eucalyptus dunnii* (3%)	625	Rutaceae	*Melicope elleryana* (4%)	656, ave
	Rhamnaceae	*Alphitonia*	*Eucalyptus robusta* (2%)	711	Rutaceae	*Flindersia pimenteliana* (4%)	470
					Rutaceae	*Flindersia schottiana* (3%)	586
					Apocynaceae	*Alstonia scholaris* (3%)	335
					Rutaceae	*Flindersia bourjotiana* (2%)	521
					Meliaceae	*Melia azedarach* (2%)	370
					Proteaceae	*Grevillea robusta* (2%)	525
Mean basic wood density (kg m^{-3})[c]		579		741			467

[a] Numbers of trees planted were obtained from CRRP records; proportion >2% are reported.
[b] >70 species commonly planted; no public records of numbers planted are available for private plantings.
[c] WD = Reported basic wood density (kg m^{-3}) (Ilic et al., 2000).

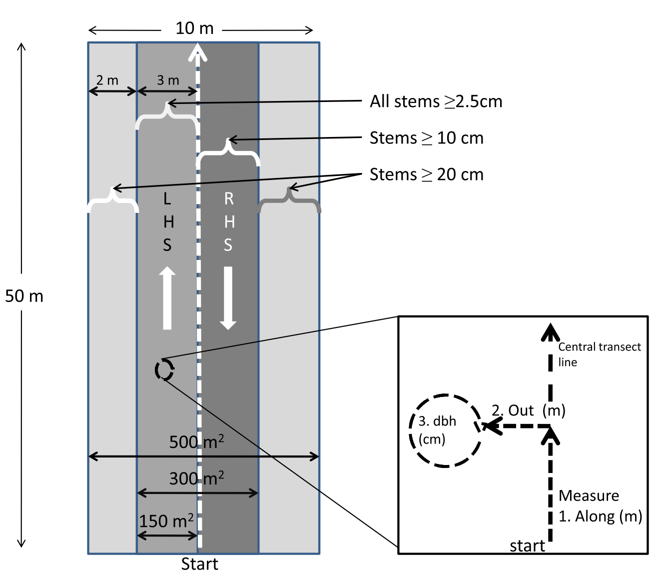

Fig. 1. Plot layouts, showing the size of nested transects and the stem sizes surveyed in each transect.

0.05 ha plot was required to ensure adequate sampling of large trees, because of their greater numbers (Pearson et al., 2005), the medium and small trees were measured from nested 0.03 and 0.015 ha subplots, respectively (Fig. 1). The results were then multiplied by the appropriate correction factor to produce per plot estimates. While sampling a number of spatially separated small plots within the large plot may be desirable to reduce auto-correlation (Stohlgren et al., 1995), in keeping with methods used across north-eastern Australia (Back et al., 1997; Back et al., 1999; Burrows et al., 2000; Burrows et al., 2002), this was not adopted here because of the additional time cost it would impose. For multi-stemmed trees, the coordinates of the central-most stem was used, and each stem was treated as a single stem for the purposes of AGB calculations. We did not include lianas in our samples, as there are no known biomass allometric functions for lianas for the bioregion.

2.3. Estimating above-ground biomass

Data were entered into an Excel workbook (Appendix 1) with built-in functions to validate data and calculate AGB, basal area and AGC (Appendix 3). The workbook retains the original order of measurements so that the location of trees in the sample plot is preserved for re-measuring in future surveys. The data from the three strata from each plot are combined and averaged to form a single replicate to avoid pseudo-replication. Trees are sorted into size classes and the AGB of measured trees within each plot is calculated using predefined allometrics. Slope is accounted for and corrected to horizontal length and area of each plot by multiplying the cosine of the slope by the transect length. The AGB per hectare for each size class is derived using a biomass expansion factor and summed to give total AGB per hectare.

To compare our estimates of AGB against the FullCAM model, we used three allometric equations: Keith's allometric developed for southern Australian rainforests, Brown's allometric and Chave's allometric. These allometrics are calculated as follows:

Keith's allometric (Keith et al., 2000; Snowdon et al., 2000):

$$\ln(\mathrm{AGB}) = -1.8967 + 2.3698 * \ln(\mathrm{dbh}) \tag{1}$$

Brown's allometric (Brown, 1997):

$$\mathrm{AGB} = \exp(-2.134 + 2.530 * \ln \mathrm{dbh}) \tag{2}$$

Chave's allometric (Chave et al., 2005):

$$\mathrm{AGB} = \rho * \exp(-1.499 + 2.148 * \mathit{ln}\ \mathit{dbh} + 0.207 * (\mathit{ln}\ \mathrm{dbh})^2 - 0.0281 * (\mathrm{lndbh})^3) \tag{3}$$

where AGB is measured in kg, dbh is measured in cm, and ρ is wood density (kg m^{-3}).

Keith's allometric was derived from Australian and international rainforest data, using direct conversion of tree dimensions (including dbh) to total biomass, and is based on stems >10 cm dbh. Brown's allometric was derived from moist tropical rainforests in Africa, Asia and Americas and developed for estimating biomass and biomass change in tropical forests, based only on stems $\geqslant$10 cm dbh. Chave's allometric was derived from international rainforest data based on 2410 trees with stems $\geqslant$5 cm dbh. As Chave's allometric includes a value for specific wood density, we used the reported rainforest default value of 500 kg m^{-3} (Department of Climate Change and Energy Efficiency 2010, p161) to conform with that assumed in FullCAM. Chave's allometric also has the capacity to adjust for tree height, but we did not use this function.

FullCAM is based on models which have been developed from studies using tree diameters $\geqslant$10 cm dbh. AlthoughFullCAM assumes a carbon fraction of 0.50 (Gifford, 2000; Richards, 2002), we adopted the valuerecommended by the Intergovernmental Panel on Climate Change (2006)for tropical forest of 0.47 (Martin and Thomas 2011), which is within the range of other estimates (Lugo and Brown, 1992; Barbosa and Fearnside, 1996; Djomo et al., 2010). To assist in the comparison of proportion of stems in each size class,we calculated basal area (BA = $(\mathrm{dbh}/200)^2 * \pi$).

2.4. FullCAM modelling tool

To obtain FullCAM estimates for each of our stands,we used the following criteria and assumptions for all of the planting types:

- plot type: multilayer mixed (forest and agricultural) system (currently the only option which will fully populate the model; Dept of Climate Change, 2008);
- the'tree yield formula' was used to model tree production;
- simulation start date:18 (environmental) or 19 (eucalypts) years before the known planting date to 'run in' the soil carbon data (Dept of Climate Change, 2008);
- forest percentage at simulation start date prior to forest establishment was assumed to be 0%;
- where necessary, assumptions that included thinning or harvesting were removed from the model;
- under the choice of 'tree-species groups' in the Data Builder step, we assigned our forest stand types to the FullCAM categories as follows: CRRP-mixed and Environmental modelled as 'mixed species environmental planting'; 'CRRP-eucalypt' modelled as '*Eucalyptus cloeziana*'.
- all other default options were accepted.

2.5. Analyses

We used ANCOVA to compare estimates of total and AGB and AGC and proportions represented in each size class using the Keith allometric between different forest types (fixed effect) and stand ages (covariate). Neither AGB nor AGC required transformation to achieve normality. Proportions were arcsin-square root transformed before analysis. In the first analysis, we treated sites as replicates ($n = 25$), including only the three planting types. We calculated mean annual increment of AGB using space (the forest stands) for time (stand age) substitution as a surrogate for time-series monitoring of individual plots. Thus, the rate of accumulation of AGB was estimated using ordinary least squares regression to regress total stand AGB against stand age, using a linear model as the best fit to the accumulation of AGB over 20 years of stand growth. The regression was forced through the origin because at time zero there is no AGB. Comparison of regression lines describing the FullCAM estimate of AGC and those of the three allometric estimates (using either all stems or medium and large stems) was achieved by testing this factor group (the different methods of estimating AGC) by the stand age covariate interaction term. All analyses were conducted using GenStat14 Edition (VSN International, 2011).

3. Results

3.1. Contribution of small stems to AGB

Across all stands, the proportion of AGB in the three size classes changed with the age of forest stand (Fig. 2; $F_{1,77} = 16.1$, $P < 0.001$). For young, planted stands most of the AGB was in small and medium stems, whereas in stands older than 15 years, most AGB was in large stems ($F_{2,32} = 7.57$, $P < 0.002$). The 18-year old stand deviated from this pattern, having a greater proportion of smaller stems, which may result from it being a regrowth stand.

The proportion of AGB among size-classes differed significantly across forest types and ages ($F_{2,78} = 22.6$, $P < 0.001$). On average, over all forest types, the small size class contained 15.1 ± 3.9%

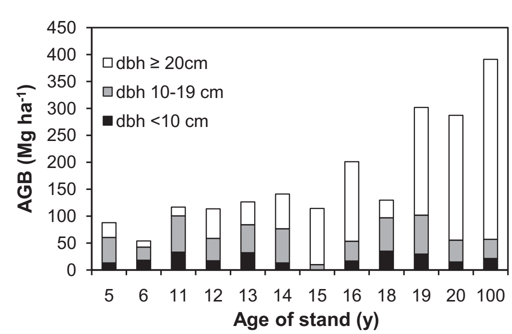

Fig. 2. Mean above-ground biomass in each size class as a function of the age of the planted stands.

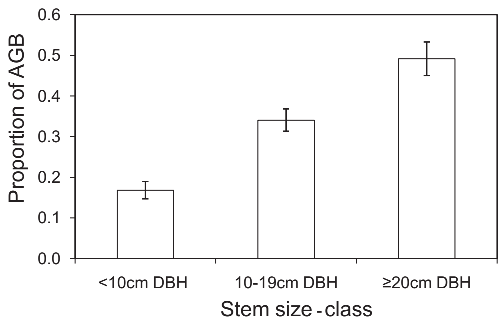

Fig. 3. Mean ± s.e. proportional contribution to AGB of trees in three size classes across all planting types.

(mean ± s.e.) of the AGB and the large size class accounted for close to half (51.6 ± 6.8%; Fig. 3).

3.2. Sequestration of biomass in stem size groups and forest types

Planted forest types did not differ in total AGB (ANCOVA $F_{2,65} = 1.2$, $P < 0.31$), but did differ in the relative contribution of each size class to AGB (ANCOVA $F_{4,65} = 2.65$, $P < 0.041$), with CRRP-Euc having the greatest proportion of AGB in large stems, and environmental plantings the highest proportion in small stems (Fig. 4). When the regrowth and remnant plot are included; plots rather than sites are used as replicates; and controlling for age, significant variation between forest types was found for both total AGB (ANCOVA $F_{4,143} = 3.2$, $P = 0.015$) and the proportion of AGB in each size class (ANCOVA $F_{10,143} = 12.6$, $P < 0.001$).

While the contribution of large stems to AGB per hectare did not differ significantly among forest types for a given age of the stand ($F_{5,35} = 2.1$, $P = 0.09$), there are some instructive trends that warrant further investigation. AGB in large stems increased with the age of the stand in all forest types ($F_{10,35} = 5.6$, $P < 0.001$), with the greatest increase in the eucalypt plantings (Fig. 5). While the AGB in environmental plantings appeared to lag behind that of other forest types in young stands, and was still roughly half that in CRRP-Euc stands at 16 years, at 16 years it had approached that of CRRP-mixed stands.

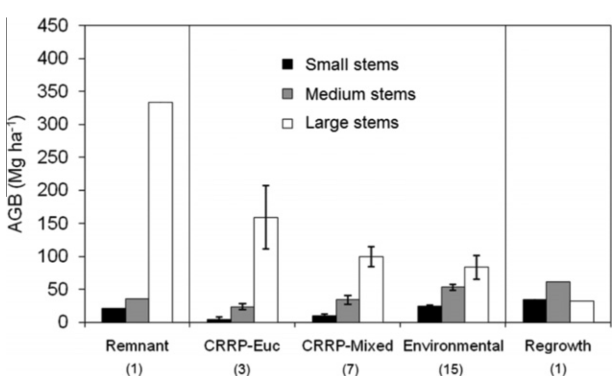

Fig. 4. Above-ground biomass (mean ± s.e.) in each size class for each forest type. Values shown in planted forest types (5–20 year old) have been age-adjusted. Number of replicates are shown in brackets.

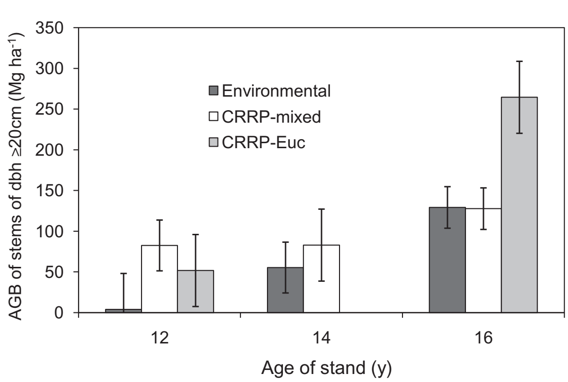

Fig. 5. Contribution of large trees to AGB (mean ± s.e.) according to age of planting.

3.3. Accumulation rates of AGB in forest plantings

Mean annual increment of AGB, averaged across all plantings was 12.084 Mg ha^{-1} y^{-1} (5.679 Mg C ha^{-1} y^{-1}; 20.846 Mg ha^{-1} y^{-1} of CO_2-e; Fig. 6).

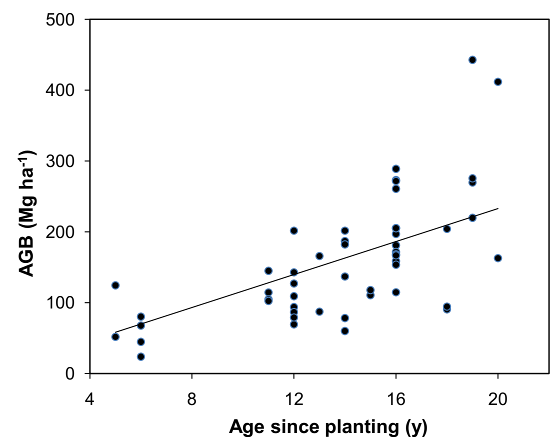

Fig. 6. Rate of AGB accumulation (Mg ha^{-1} y^{-1}) for all planting types (total AGB = 12.084*(Stand age); $F_{1,47} = 349.1$, $P < 0.001$, $R^2 = 47.6\%$).

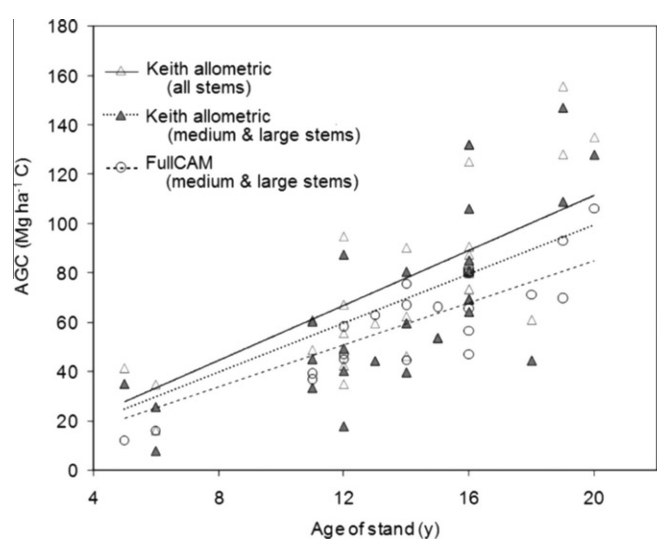

Fig. 7. Relationship between AGC as modelled in FullCAM and estimated using the Keith allometric, based on measured data, showing the contribution of all stems ⩾2.5 cm dbh, stems ⩾10 cm, and the FullCAM results which are based on studies which include only stems ⩾10 cm dbh.

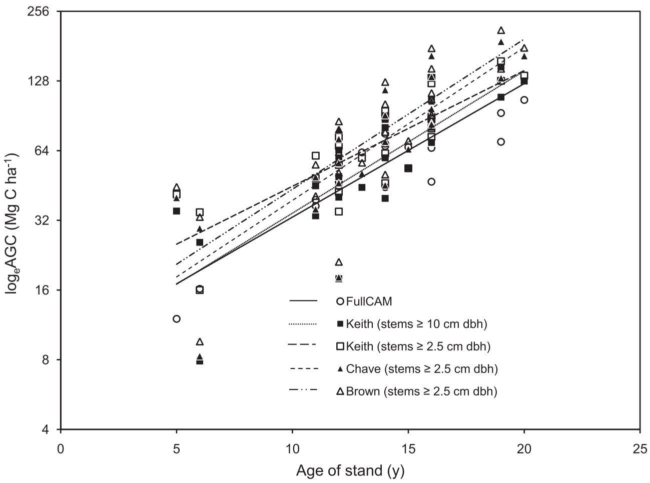

Fig. 8. Comparison of FullCAM estimates of AGC with estimates based on field data estimated from allometric functions. Note that these alternative functions were developed from data using stems ⩾10 cm dbh (Brown, 1997; Keith et al., 2000) and ⩾5 cm dbh (Chave et al., 2005) only in the estimation of AGC. We have included measured stems in the allometrics in the size classes as shown.

Inference from a linear model including only the planted forest types ($F_{4,46}$ = 13.3, P < 0.001, R^2 = 49.5%) suggests that the total AGB in the restoration plantings at approximately 14 y after planting (range = 138.6–204.1 Mg ha^{-1}, CRRP-mixed – CRRP-euc, respectively) is about half that of forest remnants of indeterminate age (mean AGB ± s.e. = 390.9 ± 43.3 Mg ha^{-1}) and three times the biomass of 18-year old regrowth forests (61.3 ± 36.7 Mg ha^{-1}). Estimates based on a fitted quadratic function, typically used to approximate the accumulation of biomass with age (Grierson et al., 1992), did not differ significantly from the linear trends reported above (at 14 y, range = 117.5–204.1 Mg ha^{-1}).

3.4. Comparison between measured and modelled carbon sequestration

Using data from all planted stands (n = 25) and all size classes, the Keith allometric estimate of AGC for a mean-aged stand (13.6 y; mean ± s.e., 77.4 ± 4.5 Mg C ha^{-1}), was 19.5% greater than that derived from FullCAM (57.9 ± 2.3 Mg Cha^{-1}; Fig. 7). On a site-by-site basis, using the differences between the estimates modelled from FullCAM and those estimated from the Keith allometric, the estimates from the Keith allometric were on average 17.8 ± 6.4% greater than those generated from FullCAM ($F_{2,71}$ = 5.7, P < 0.01). Estimates from FullCAM were lower than estimates from field data using the Keith allometric in approximately two-thirds of sites and higher in the remaining one third.

Comparing our estimates of AGC with estimates derived from the two allometric functions developed specifically for moist tropical forest and the one developed by Keith et al. (2000), our field data show that the FullCAM model consistently underestimated the AGC by 17.8% to 54.9% (Fig. 8; $F_{4,119}$ = 5.9, P < 0.001, and Table 2). When small stems were excluded, FullCAM estimates were on average 9.0% lower than estimates produced using the Keith allometric; 25.3% lower than estimates produced using the Chave allometric; and 31.9% lower than estimates produced using the Brown allometric.

4. Discussion

4.1. Contribution of small stems to AGB

Current carbon accounting procedures neither specify a minimum stem diameter nor a standardised sampling method (Australian Greenhouse Office, 2002;Research Working Group #2, 1999). In fact, the Australian Forest Mensuration code suggests that small stems may be ignored (Research Working Group #2, 1999). As we have shown, this significantly underestimates the proportion of AGB (by 15.1 ± 3.9% in our case) stored in a forest, and as we are interested in total coarse wood productivity (Malhi et al. 2004), they should be included in estimates. Hedl et al. (2009) also found that small stems comprised as much as 50% of the stems in a stand, and Djomo et al. (2011) found an average 8% of the carbon current annual increment was in this size class. Quite how many stems are in this small size class is dependent on the successional age of the stand, but in most instances these small stems contribute significantly to the carbon pool (Brown, 2002). We demonstrate that small stems should be included in estimates of AGB, especially in younger forests where they may be abundant.

4.2. Forestry plantations versus environmental plantings

Across all planting types and ages, we found that up to 14 years after planting, forestry plantings had a slightly higher proportion of large trees and higher total AGB when compared with environmental plantings, but this difference disappeared as forests aged. All planted forests had most of their AGB in large trees, with the forestry spacings (such as in the CRRP forests) producing more in this size class. This has significance for carbon sequestration potential and economic returns, especially in the first 15 to 20 years of the plantings.

Eucalyptus forestry plantings sequestered more AGB, and therefore carbon, than did mixed-species environmental plantings and forestry plantings. However, while eucalypt plantings sequester more carbon more quickly in the first few years, planting them in areas that were previously rainforest potentially diminishes the biodiversity gains of restoration forestry. Planting forests for carbon, biodiversity and timber could result in different and sometimes conflicting outcomes. It is well-known, for instance, that spacing trees too closely together reduces the stem radial growth increment, which reduces the volume of harvestable timber (Evans and Turnbull, 2004) and thus the amount of carbon sequestered. Wider tree spacingsof 3 to 4 m, which is common in forestry plantings, is an optimal spacing and should sequester more carbon in tree stems, but could arguably yield lower biodiversity benefits (Erskine and Catterall, 2004). However, because all forest stands provide habitat for forest species to some degree (e.g. Jansen, 2005; Chazdon et al., 2009), the biodiversity benefits are likely to be affected more by the species of trees planted than tree spacing.

Table 2
Comparison of FullCAM estimates of AGC with estimates produced using allometric functions, as both absolute and relative values (mean ± s.e.), and including and excluding small stems (mean, s.e.).

Source	FullCAM	Keith et al. (2000)	Keith et al. (2000)	Chave et al. (2005)	Brown (1997)
Stems	⩾10 cm	⩾10 cm	⩾2.5 cm	⩾5 cm	⩾10 cm
AGC (Mg C ha^{-1})	63.5 ± 5.8	69.8 ± 7.9	79.0 ± 7.8	85.0 ± 10.4	93.3 ± 11.2

4.3. Comparisons of AGC estimates between the rainforest biomass allometric functions and FullCAM

FullCAM estimates across all planted sites were significantly lower than estimates based on our measurements (Table 2). The variation about these estimates is reasonably large, and is likely due to the variation in stand type, dbh, AGB, BA, species and management regimes, and characteristic of the planted stands (Nightingale et al., 2008). The models on which FullCAM is based mostly ignore stems < 10 cm dbh, as do the allometric functions developed by Keith et al. (2000) and Brown (1997), whereas Chave et al. (2005) included stems ⩾5 cm dbh. In relatively young forest stands, such as the environmental and community plantings investigated here, models that exclude stems <10 cm dbh are not appropriate for carbon accounting.

This is an important consideration for landholders wishing to obtain remuneration for the carbon sequestered in environmental plantings.We suggest that the allometric function developed by Chave et al. (2005) be used for Australian tropical forests and until a new allometric function is developed for Australian wet and moist tropical rainforests to replace Keith et al. (2000). The new allometric functions should be calibrated against a range of sites and estimates of errors should be included. We recommend, however, that Chave's allometric function be used with caution as Djomo et al. (2010) found that although it produced reasonable estimates for Cameroonian forests, even though it includes no data from Africa, better estimates could be obtained from including site-specific diameter, height and wood density. Basuki et al. (2009) found significant discrepancies between estimates using general tropical rainforest allometric functions and their own estimates for forests in Kalimantan. The only study in the Wet Tropics (Liddell et al. 2007), which provides calibration with these models, found that the Chave et al. (2005) estimates produced results very close to those derived from their Wet Tropics lowland tropical rainforest data.

4.4. Some observations on FullCAM

Deficiencies in the parameterisation of the FullCAM model and the incorporated rainforest allometric function influence the carbon estimate. Most notably:

(1) The FullCAM model is based on CAMFor, which in turn uses a variant of the *3-PG* model (Landsberg and Waring, 1997) to incorporate a forest productivity index in the estimates of AGB, The latter, however, does not account for the very wide range of productivity valuesin the Wet Tropics(Kesteven et al., 2004);

(2) Mean annual volume increments are estimated for each region and are not derived from the growth rates of the most common species (Waterworth et al., 2007). For North Queensland, volume estimates from only Eucalypt plantations and Hoop Pine *Araucaria cunninghamii* plantations were included in the FullCAM database, so estimates of AGB vary widely among sites and forest types. FullCAM also assumes that the age of maximum annual increment for stem volume is within the range 12-20 years 'for most species' (Department of Climate Change and Energy Efficiency 2010; p162), and this assumption is derived from growth models of only six species of plantation eucalypts in southern Australia (West and Mattay, 2003).Thus, tree growth rates determined for Australia's National Forest Inventory, which inform the modelling done in FullCAM(Department of Climate Change and Energy Efficiency, 2010), are not age-based growth curves for rainforests;

(3) The FullCAM model also assumes that environmental and amenity plantings are the same as regenerating forests and therefore are treated as having no management or species effects, whereas the accumulation of AGB in *Eucalypt* plantations is clearly driven by management effects (Waterworth et al., 2007). Management effects should be included in Full-CAM for environmental plantings, as most of them are managed;

(4) The modelling of AGB in natural regrowthin FullCAM is also likely to be inaccurate as it is based on a simple empirical growth model from limited field data and excludes young (undefined) regrowth (Department of Climate Change and Energy Efficiency, 2010);

(5) Wood density for Wet Tropic rainforest species is assumed to be 500 kg m^{-3}in NCAS. However, Ilic et al. (2000) and more recent data (D. Metcalfe, pers. comm. 2011) suggest that the mean is closer to 570-580 kg m^{-3}, which is the same value (580 kg m^{-3}) used by Chave et al. (2004) where

Table 3
Comparison of rates of AGC accumulation from other tropical forests with Australian Wet Tropics.

Location of study	Age of stands (y)	Assumed carbon fraction of AGB[a]	Min stem dbh (cm)	Annual AGB accumulation rate (Mg ha^{-1} y^{-1})	Annual AGC accumulation rate (Mg C ha^{-1} y^{-1})	Source
Wet Tropics, Australia	5–20	0.47	2.5	12.08	5.68	This study
Kalimantan Heath Forest	Disturbed	(0.5)	4.8	8.1–8.5	4.0–4.25	Miyamoto et al. (2007)
Ecuador (>3000 m ASL)	8 and 6	(0.5)	3.0	14.2–15.0	7.1–7.5	Fehse et al. (2002)
Costa Rica	4–20	0.47	2.5	7.85	3.69	Fonseca et al. (2011)
Ecuador (>3000 m ASL)	30	(0.5)	3.0	5.9–6.9	2.9–3.5	Fehse et al. (2002)
Cameroon agro-forests	Disturbed	0.47	5.0		2.54 ± 0.65	Djomo et al. (2011)
Cameroon managed forests	Disturbed	0.47	5.0		2.79 ± 0.72	Djomo et al. (2011)
Cameroon national park forests	Mature (?)	0.47	5.0		2.85 ± 0.72	Djomo et al. (2011)
Sulawesi (1000 m)	Mature	(0.45)	2	13.1 ± 0.6	5.8 ± 0.3	Hertel et al. (2009)[b]
Paleotropical	Mature	(0.5)	2	11.4 ± 1.3	5.7	Hertel et al. (2009)
Amazonia – Manaus	Mature (?)	Not stated	10?		3.58[c]	Malhi et al. (2009)
Amazonia – Tapajos	Mature (?)	Not stated	10		4.76[c]	Malhi et al. (2009)
Amazonia – Caxiuana	Mature (?)	Not stated	10		3.16[c]	Malhi et al. (2009)
Neotropical forests	Old-growth	0.5	10		1.5–5.5	Malhi et al. (2004)
Amazonia	Old-growth	0.5	10	0.98 ± 0.38	0.49	Baker et al. (2004)
African tropical forests	Mature	0.5	10		0.63	Lewis et al. (2009)

[a] Parentheses indicate not reported in literature.
[b] Average at one location over 1 year.
[c] Derived by adding branch and trunk rates.

species-specific values were not available. We recommend an adjustment of the value for wood density used in the FullCAM model to 580 kg m^{-3};

(6) FullCAM assumes that the carbon sequestration rate of mature rainforests is constant at 0.58 Mg C ha^{-1} y^{-1}, but no data are reported for growth rates in rainforests in the three age classes of 1-10, 11-30 and 31-100 years, in contrast with eucalypt and other forest types. Research on this aspect is needed;

(7) Prior to 2008, 3-PG had not been tested for tropical rainforests in the Australian Wet Tropics (Nightingale et al., 2008). Although parameterisation and calibration of the 3-PG model for restored rainforest, and the related 3-PGS for old-growth tropical rainforest (Coops et al., 1998), has been undertaken using data obtained from tree measurements, these have not yet been integrated into FullCAM. Thus, the 3-PG model underestimates dbh, basal area and AGB values for the Wet Tropics (Nightingale et al., 2008, p115). The challenge to improving 3-PG and FullCAM is in including the wide range of forest types and ages in the Wet Tropics.

4.5. Comparisons of Carbon sequestration rates among tropical forests

The average annual rate of accumulation of AGC derived using the Keith et al. (2000) allometric is within the range of other moist tropical forests, bearing in mind that the assumed carbon fraction varies between 0.45 and 0.5 among the estimates (Table 3).

5. Conclusions

Carbon sequestration is now recognised as an ecosystem service (Turner et al. 2011) and revenue from carbon credits from rainforest stands could promote reforestation for biodiversity conservation on private land in north-eastern Queensland, Australia. Carbon credits couldbe earned whether forests are native regrowth, remnant stands or environmental plantings. However, to engage with the carbon economy landowners must be able to estimate accurately the carbon sequestered in their forests. Unfortunately, in Australia the current models and allometric functions for estimating carbon in tropical rainforests are not calibrated against local sites and tree growth rates and volumes from the tropics.

Our study demonstrates the inadequacy of current methods for estimating carbon stocks in rainforest and environmental plantings in north-eastern Queensland. Current estimates clearly deprive landholders of financial incentives and underestimate the national greenhouse gas benefits of tree planting in the wet tropics. A tailored biomass allometric and the re-parameterisation of FullCAM are needed. Until then, we recommend the Chave et al. (2005) allometric function, which provides intermediate values, is based on the widest range of tropical trees, and has been shown to be accurate away from the sites used for its development (Djomo et al. 2010; Liddell et al. 2007).

Using a modified plot-based mensuration method, which is quick and economical to alto establish and monitor in small and large tropical forests, we were able to demonstrate that small stems < 10 cm dbh contribute substantially to total AGB (15.1 ± 3.9%) and should be included in future carbon accounting methods. Our inventories of planted forests in the Wet Tropics further show that the FullCAM model underestimates the AGC in forest by significant amounts. Based on our modelling, forestry type plantations are just as effective as environmental plantings in sequestering carbon, and show equivalent growth rates overall, but significantly greater radial growth over the first 15 years of growth. Forestry type plantations are much cheaper to establish, as only one third as many seedlings are required to be planted. Appropriate mixes of species that optimise biodiversity could make forestry-type plantations a very effective method of restoring forests in agricultural landscapes.

These findings are dependent on the adequacy of the allometric function used to estimate AGC. The allometric function published by the Australian government for rainforests estimates higher carbon sequestration rates than does the FullCAM model, but lower than the pan-tropical allometric function developed by Chave et al. (2005). Although the Chave et al. (2005) allometric function has not been adjusted for Australian rainforests, it has been used in at least two widely different rainforest locations and found to be reliable. We recommend that their allometric function be used in preference to the currently applied allometric function by Keith et al. (2000). To achieve accurate estimates of the AGC sequestered in trees in the Wet Tropics more thorough forest mensuration from many more sites, using actual tree volumes and wood densities, is required to improve the allometric equations used in modelling primary production. The data and assumptions used in NCAS that urgently need to be revised include the age-incremental growth models; the assumed carbon fraction in wood; and the assumed average wood density. A revised 3-PG model for the Wet Tropics should be incorporated.

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