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CORRESPONDENCE

Authors' response to the correspondence by Dr. Janaka Ratnasiri on the Research Article:

Estimation of carbon stocks in the forest plantations of Sri Lanka by De Costa, W.A.J.M. & Suranga, H.R. JNSF 40(1): 9-41.

In the above paper, the merchantable wood volume of different plantation forest tree species was converted to above-ground biomass and carbon stock per ha, using the procedure followed by Cost *et al*. (1990), Sampson (1992) and Birdsey (1992) in the estimation of total forest biomass of the USA, which was conducted by the American Forestry Society. This procedure used a common wood density value of 490 kg m^{-3}, which was an average value across all tree species involved.

Any measurement or an estimate of any variable has a measurement/estimation error associated with it. Possible errors associated with our estimates of carbon stocks of Sri Lankan forest plantations owing to the use of a common value of wood density are negligible in comparison to the magnitude of errors associated with published measurements of forest carbon fluxes and our estimates of carbon stocks are well-within the uncertainty levels that are acceptable to the Intergovernmental Panel on Climate Change (IPCC). We have also examined briefly the biological and environmental factors that determine the process of wood formation and consequent determination of wood density and showed that there is likely to be intra-species variation of wood density, which can be in the same order of magnitude as the inter-species variation. Accordingly, the adjusting of our carbon stock estimates based on inter-species variation of wood density without taking into consideration the intra-species variation, would not improve the precision of our estimates significantly.

(a) Magnitude of possible errors associated with the estimates of carbon stocks

Our study shows that 92 % of the 57,618.8 ha area of monoculture forest plantations in Sri Lanka is planted with five tree species, namely, *Pinus caribaea*, *Tectona grandis*, *Eucalyptus grandis*, *Eucalyptus camaldulensis* and *Swietenia macrophylla*. The reported wood densities of tropical tree species were obtained from the following three sources, all of which are widely-recognized and cited:

(1) Volume 4 (Agriculture, Forestry and Other Land Use) of the IPCC Guidelines for National Greenhouse Gas Inventories published in 2006 (IPCC, 2006). Institute for Global Environmental Strategies, Kanagawa, Japan.
(2) Brown S. (1997). FAO forestry paper – 134: *Estimating Biomass and Biomass Change in Tropical Forests: A Primer.* Food and Agriculture Organization, Rome, Italy.
(3) Reyes G., Brown S., Chapman J. & Lugo A.E. (1992). Wood densities of tropical tree Species. *General Technical Report SO-88*. Forest Service, Southern Forest Experiment Station, US Department of Agriculture, New Orleans, Louisianna, USA.

The values in Table 1 can be compared with the value of 490 kg m^{-3} used in our study. These comparisons can be done within the context of the theoretical and observed ranges of wood densities for tree species. Theoretically, wood density can vary from 0 to 1500 kg m^{-3} (Chave *et al*., 2009). The upper limit signifies the density of woody structures, excluding open spaces within wood. Chave *et al*. (2006) observed a range between 110 and 1390 kg m^{-3}, for 2456 Neotropical tree species. Although Neotropics do not exactly match the climatic conditions found in Sri Lanka, the above range is indicative of the range of inter-species variation of wood densities present. It is also notable that Chave *et al*. (2006) found standard deviations of ± 180 kg m^{-3} around mean wood densities. The above range and standard deviations of wood densities can be considered as benchmarks to decide whether the reported

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Table 1: Wood densities reported in Reyes *et al*. (1992) for tree species and genera, which form more than 95 % of the monoculture forest plantations and more than 85 % of the mixed culture forest plantations in Sri Lanka

Tree species	Wood density (kg m^{-3})
Pinus caribaea	480 (Tropical Asia)
Tectona grandis	500, 550 (Two values are reported for Tropical Asia)
Swietenia macrophylla	490, 530 (Two values are reported for Tropical Asia)
Swietenia macrophylla	420, 450, 460, 540 (Four values are reported for Tropical America)
Eucalyptus grandis	Not reported in Reyes *et al*. (1992)
Eucalyptus camaldulensis	Not reported in Reyes *et al*. (1992)
Eucalyptus citriodora	640 (Tropical Asia)
Eucalyptus deglupta	340 (Tropical Asia)
Eucalyptus robusta	510 (Tropical America)

wood densities of the tree species listed in Table 1 deviate significantly from the single average value used for this study.

The value for *Pinus caribaea* (i.e. 480 kg m^{-3}) used by Reyes *et al*. (1992) is very close to the value of 490 kg m^{-3} used by us. So is the average of the two values reported for *Tectona grandis* (i.e. 525 kg m^{-3}). For *Swietenia macrophylla*, the average of the two values reported for Tropical Asia (i.e. 510 kg m^{-3}) is again very close to our value. The average of all six values reported for *Swietenia macrophylla* (i.e. 482 kg m^{-3}), which takes into account the values reported for Tropical America as well, is even closer to our value.

In an in-depth statistical analysis of wood densities, Chave *et al*. (2006) have shown that genus level means give reliable approximations of wood densities of species, for which data are not available. Following this principle, a wood density estimate can be calculated for *Eucalyptus grandis* and *E. camaldulensis* using reported values for *E. citriodora, E. deglupta* and *E. robusta*. The calculated mean for the two species from Tropical Asia gives 490 kg m^{-3}, which exactly matches the value that has been used in our study. Even when the value reported for *E. robusta* (coming from Tropical America) is included in the calculation of genus level mean, the calculated mean (i.e. 497 kg m^{-3}) is very closer to our value.

The mean wood densities of the genera *Pinus*, *Eucalyptus*, *Tectona* and *Swietenia* as reported in Reyes *et al*. (1992), are in close agreement with the single average value of 490 kg m^{-3} that has been used by De Costa & Suranga (2012). Therefore, it is our considered opinion that using a single average wood density has not caused a significant error that warrants a fresh calculation.

(b) Suitability of the carbon stock estimates to be used in negotiations on climate change mitigation options

All IPCC reports and internationally-published literature on greenhouse gas emissions, carbon sequestration and components of the global carbon balance, report errors, which are often 50 – 100 % of the estimated mean values. In view of the magnitudes of errors involved in the above literature, which is published by the IPCC and is based on the work of eminent scientists in this particular field of study, it is our considered opinion that the magnitude of error involved in our calculation (which has been shown to be insignificant in the preceding section) does not in any way disqualify our carbon stock estimates from being used by Sri Lankan scientists, policy makers and consultants in international negotiations on climate change mitigation options.

These magnitudes of errors, which are often 50 - 100 % of the estimated mean values even in carbon flux estimates of forests are accepted by the IPCC and the international scientific community because of: (a) the extremely complex nature of forest ecosystems and their growing environments; (b) the complexity of the physical and physiological processes that are taking place in these ecosystems and the spatial and temporal variation of the rates of these processes; and (c) the levels of accuracy and precision of the methods of measurement and estimation that are currently available.

(c) Biological and environmental factors determining the wood density and its inter- and intra-species variation

The issue on wood density and its possible variation that is raised in this correspondence also prompted us to take a closer look at the biological processes responsible for wood formation and the consequent determination of wood density and its possible variation. The physiological processes that are involved in wood formation shows that use of species-specific wood densities would not improve the precision of carbon stock estimates, unless the intra-species variation of wood density, which can be of the same order of magnitude as the narrow range of inter-species variation observed for the major plantation forest tree species grown in Sri Lanka (Reyes *et al*., 1992), is also taken in to consideration. Physiological processes of wood formation involves cell division and expansion in the trunk of a tree, translocation of primary carbohydrates to the stem, formation of lignin and other wood components (i.e. stilbene, flavonoid derivatives etc.) from primary carbohydrates and deposition of lignin in the woody tissue that is being formed. All the above processes are significantly influenced by environmental conditions in the growing environment of the trees (Swenson & Enquist, 2007; Chave *et al*., 2006, 2009). These include solar radiation intensity, water availability (as determined by rainfall and evapotranspiration), nutrient availability (as determined by soil chemical and physical properties) and other soil properties such as acidity, depth etc.. For example, Chave *et al*. (2006) have shown that wood density varies with numerous morphological, mechanical, physiological and economic properties. They showed that wood density decreased with increasing altitude and water availability. Our work included forest plantations growing across a wide range of agroecological regions of Sri Lanka, which varied significantly in terms of altitude, water availability, nutrient availability, solar radiation receipt and soil properties. Therefore, it is highly likely that there is significant intra-species variation in wood density, which is likely to be of the same order of magnitude as its inter-species variation.

Another related issue is the question of how representative the species-specific wood densities reported in literature are of the wood density of different parts of a tree. Chave *et al*. (2009) observed that wood density can vary even within an individual tree and that foresters typically measure the density of heartwood, which is higher than the density of sapwood (Woodcock & Shier, 2002; Patiño *et al*., 2008). Furthermore, wood density of an individual tree varies with height (Swenson & Enquist, 2007) and age (Chave *et al*., 2009). It is also reported that wood density of roots is lower than that of above-ground parts (Pratt *et al*., 2007). Carbon that is stored in all parts of a tree has to be taken into account in carbon stock calculations and hence ideally needs a weighted average wood density. It is doubtful whether the reported species-specific wood densities are such weighted averages.

In view of the above sources of variation of wood density even within a given tree species, it is the considered opinion of the authors that without a proper accounting of the intra-species variation of wood density, adjustment of our carbon stock estimates based on species-specific average wood densities would not improve their precision significantly. We would merely be moving within the same confidence interval as defined by the overall error involved in our calculations.

A careful reading of the Methods and Materials section of our Research Article have shown the possible errors and uncertainties involved in different steps of the carbon stock calculation procedure that had been adopted. The conclusion has clearly stated that the estimates are approximate and that they can be considered as lower-boundary estimates. It has been further stated that the estimates can be fine tuned and made more accurate by updating the FORDATA database, increasing the frequency of measurements of DBH and height and by developing allometric relationships for plantation forest species for which they are not available. Incorporation of species-specific wood density values in these calculations is part of that fine tuning exercise. As we have demonstrated in this response, within the context of the possible magnitude of errors involved in our study and the magnitude of errors associated with the published values of forest carbon fluxes, this requirement for fine tuning does not in any way invalidate the carbon stock estimates.

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