

ARE TROPICAL FORESTS AN IMPORTANT CARBON SINK? REANALYSIS OF THE LONG-TERM PLOT DATA

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Abstract. In a recent (1998) publication of *Science*, data from a large number of forest inventory plots were used to estimate biomass trends in old-growth tropical forests. Although no evidence was found of net biomass change in mature Paleotropical forests, old growth of the humid Neotropics was inferred to have been a substantial biomass carbon sink in recent decades. Methodological artifacts affected this analysis, however. Many humid Neotropical plots were measured strictly at breast height, where tropical trees frequently have buttresses and other protruberances. Because biomass allometric equations are based on above-buttress tree diameters, and because bole irregularities show disproportionately rapid radial increments, estimates of biomass and biomass increase must be based on above-buttress measurements. In addition, some plots were on recent floodplains, where forests undergo biomass accretion during primary succession.

The data set includes 25 sites from the humid lowland Neotropics that were measured above buttresses with standard techniques and that were not on recent floodplains. Mean estimated biomass change for these sites was $0.3 \text{ Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$, with a 95% confidence interval including 0.0 (-0.3 to $+0.9 \text{ Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$). While the *Science* study was a laudable attempt to address an important aspect of the global carbon budget, the underlying data do not indicate a significant biomass carbon sink in old-growth forests of the humid Neotropics.

Key words: biomass, tropical forests; buttresses; carbon sinks, global; global carbon budget; Neotropical forests; old-growth forest; tree growth; tropical rain forest.

INTRODUCTION

The anthropogenic increase in atmospheric carbon dioxide (Petit et al. 1999) will have profound effects on global climate (cf. Crowley 2000) and terrestrial and oceanic ecosystems (Denman et al. 1996, Melillo et al. 1996). A critical research need is to improve understanding of the global carbon budget. One important uncertainty is the “missing carbon sink,” the $0.5\text{--}1.9 \text{ Pg}$ ($=10^{15} \text{ g}$) difference in the 1980s between the net annual anthropogenic addition of carbon to the atmosphere, and the annual sum of the net increase in atmospheric carbon and estimated net oceanic uptake (Schimel 1995, Melillo et al. 1996). Tropical rain forests are a logical place to look for this carbon. Highly productive, they are estimated to account for 32% (Field et al. 1998) to 36% (Melillo et al. 1993) of the world’s potential terrestrial net primary production (NPP). If total photosynthesis exceeds total respiration in these forests, the imbalance could represent a very large net uptake of carbon by these ecosystems. The net carbon exchange between tropical forests and the atmosphere has been little studied and is currently debated. Eddy covariance data from three Amazonian sites (Fan et al. 1990, Grace et al. 1995, Mahli et al.

1998) have suggested that mature tropical moist forests are significant carbon sinks (but see Keller et al. 1996, Mahli and Grace 2000). Other recent studies, however, indicate that NPP reductions in these forests due to lowered soil moisture or increased temperature (Kindermann et al. 1996, Braswell et al. 1997, Tian et al. 1998, Cox et al. 2000, White et al. 2000; D. A. Clark, S. C. Piper, C. D. Keeling, and D. B. Clark, *unpublished manuscript*) could make them net carbon sources.

Recently Phillips et al. (1998a) addressed this important question by collating and analyzing a large number of data sets from tropical forest inventory plots around the world. From repeated measurements of all trees, they estimated the aboveground biomass in each plot at the beginning and end of each census interval. The plots were active during different times and for different-length census intervals during 1947–1997. Phillips et al. combined them by linearly interpolating the estimated annual biomass changes and averaging these for all active plots in each year of this period. While their analysis indicated that there has been no significant change in aboveground biomass in African and Asian tropical forests, it appeared to provide evidence of a substantial increase ($1.11 \pm 0.54 \text{ Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ [mean \pm 95% CI]) in aboveground forest biomass in the humid Neotropics, particularly in the lowlands. After increasing this figure by 33% to account for their estimate of additional biomass increase belowground, Phillips et al. multiplied the result by the estimated carbon content of forest biomass and forest

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area in the humid Neotropics. This calculation suggested that old-growth lowland forests in this region have been acting as a net biomass carbon sink of 0.52 ± 0.28 Pg C/yr, a substantial proportion of the global "missing carbon." This finding has affected current thinking about the world carbon budget, and it has been widely cited (cf. Mahli and Grace 2000), particularly as corroborating recent eddy flux studies in the Amazon.

By collating many data sets from tropical forest inventory plots, a number of them unpublished, Phillips et al. (1998a) performed a valuable service. Their study was also laudable in attempting to provide a ballpark estimate of recent historical biomass changes in tropical forests. The types of simplifying assumptions and averaging they used will frequently be required for such exercises. When the assumptions are reasonable and the underlying data unbiased, such calculations can improve understanding of the global carbon budget.

A reanalysis of the data set used in Phillips et al. (1998a), however, calls into question the central conclusion of the study, that during recent decades old-growth forests in the humid Neotropics have been accumulating substantial amounts of carbon in the form of net biomass increases. When account is taken of methodological artifacts, the inventory plot data do not indicate such biomass accumulation. In this paper I reanalyze the data and discuss the methods issues and their implications for assessing the biomass dynamics of old-growth tropical forests.

TREE-MEASUREMENT METHODS AND PLOT SUCCESSIONAL STATUS

A number of the Neotropical inventory plots used in the Phillips et al. (1998a) analysis (see Phillips et al. [1998b] for site documentation) involved methodological problems. The first has to do with how trees were measured. The second relates to the likelihood of stands being successional rather than mature. Because all five montane Neotropical sites presented the first problem (see below), that type of Neotropical forest cannot be analyzed for biomass trends. I restrict the following analysis to the large sample of plots from the lowland humid Neotropics.

Inappropriate tree-measurement methods strongly affected the results of Phillips et al. (1998a). In tropical forests, many trees have protruberances (buttresses, stilt roots, other irregularities) on the boles at "breast height" (1.3–1.4 m above the ground), the standard measurement height in temperate forests. In the tropics, the diameter of a tree's cylindrical bole must be measured above such protruberances, often ≥ 3 m above the ground. It is this diameter that is used to calculate stand-level basal area (BA), the summed cross-sectional area of all trees above a preselected minimum diameter. When tropical forest BA is based on measuring all trees at breast height, it can be greatly inflated. In an Ugandan rain-forest plot measured both

ways, the around-buttress measurement (all trees at breast height) produced a BA that was twice the correctly measured value (Sheil 1995). Similarly, when aboveground biomass is estimated from an allometric equation relating biomass to tree diameters or BA (as in Phillips et al. 1998a), the biomass estimation requires tree measurements above any major stem irregularities. Tree biomass allometries are derived by harvesting trees, determining their dry biomass, and relating that biomass to their cylindrical bole diameter (Brown 1997). When stand-level aboveground biomass is estimated by measuring all trees at breast height and then applying the biomass allometry, it will be greatly overestimated (100% at the Uganda site, Sheil 1995; 43% at La Selva, Costa Rica, Clark and Clark 2000a). When the metric of interest is the change in stand biomass over a census interval, the disproportionately rapid radial increments of buttresses and other bole irregularities (Sheil 1995) will compound the overestimation of biomass increase. Bole irregularities occur frequently through the entire size range of trees measured in most tropical forest inventory plots (≥ 10 cm diameter) and are not an issue just for a few large trees per plot. In 12 0.5-ha inventory plots in a Costa Rican lowland rain forest (Clark and Clark 2000a), basal irregularities made it necessary to use ladders to measure diameter at heights of 3–6 m for an average of 25% of stems in each plot, representing all size classes (12%, 71%, and 97% of trees 10–30 cm, 30–50 cm, and > 50 cm in diameter, respectively), and these ladder-measured trees accounted for 52% of the stand-level biomass increment (D. B. Clark and D. A. Clark, *unpublished data*). Measuring them at breast height would have led to a large overestimate of forest biomass increase.

Although measurement above buttresses was a stated criterion in the analysis (Phillips et al. 1998a), for 11 lowland Neotropical sites (Sites 1, 15, 21–22, 35–38, 39, 44–45) the available evidence indicates that measurements were not adjusted to avoid such stem irregularities. The published methods for these plots (Gentry and Terborgh 1990; also, citations in Phillips et al. 1998b) state that trees were all measured at breast height and give no accompanying statement that other measurement heights were used for trees with bole irregularities. For six of these sites (Sites 35–38 and 44–45, as well as the five Montane sites mentioned earlier) the author provided very detailed methods (Veillon 1985, *personal communication*). Emphasizing standardization, he measured all trees at 1.3 m above the ground; he documented resulting problems by characterizing each measurement as "good," "ok," or "bad" ("buena, regular y mala," Veillon 1985: 22). In the case of a few trees in his 62 forest inventory plots ("unos pocos casos," Veillon 1985: 22), the tree had such high buttresses or extreme stem malformation that he did not measure it and instead applied to it the mean increment for its diameter class. For Sites 21 and

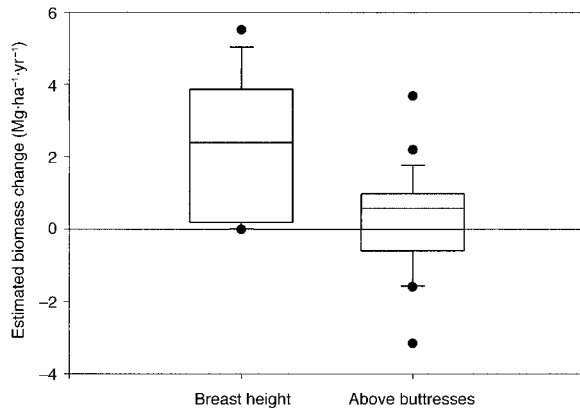


FIG. 1. The estimated change in aboveground biomass (Phillips et al. 1998a) for the 11 Neotropical lowland humid forest plots in which all trees were measured at breast height ("Breast height") and the 25 plots (not on recent floodplains) where trees were measured above buttresses with standard methods ("Above buttresses"). (For plot documentation see Phillips et al. 1998b.) Boxplots indicate quartiles on either side of the median and outliers.

22, in addition to the published methods stating that trees were all measured at 1.3 m height, the author confirmed that no ladders were used (J. Terborgh, *personal communication*). Fig. 1 ("Breast height") shows the estimated biomass increases for these 11 lowland Neotropical sites (mean increase = 2.2 Mg·ha⁻¹·yr⁻¹). No plot decreased in biomass, and for seven plots the estimated biomass increase was large: 1.6–5.5 Mg·ha⁻¹·yr⁻¹.

A second problematic group are three plots apparently measured above buttresses but located on young Amazonian floodplains ("Recent Floodplain" as opposed to "Mature Floodplain" and "Old Floodplain" in the site listing; Sites 18, 19, and 29). The process of forest development through primary succession on newly deposited river terraces in Amazonia is well documented (cf. Foster 1990). Although these plots were judged to be mature forest (O. L. Phillips, *personal communication*), it is not possible to determine by inspection that a stand is no longer undergoing successional increase in biomass. The rates of biomass increase (2.7, 2.1, and -0.4 Mg·ha⁻¹·yr⁻¹, respectively) suggest that two of these stands were still strongly accreting biomass. Because young floodplains contain a mix of stands, many still undergoing succession, plots on these soils should be excluded from analyses of biomass change in tropical mature forests, unless data convincingly show that they are no longer successional.

The plots that were documented as having been measured above buttresses and that were not on recent floodplains present a very different picture of biomass change in the humid Neotropical lowlands. This group of 27 sites excludes three for which the published methods gave no clear information about the height of tree measurement (Sites 11, 40, and 41), as well as Site 42,

where all measurements were first at breast height and then changed to above buttresses (Lieberman and Lieberman 1987, 1994). For these 27 sites, the mean estimated biomass change is 0.7 Mg·ha⁻¹·yr⁻¹, with a 95% confidence interval that includes 0, and with seven sites showing net biomass loss. This reanalysis includes two outliers in terms of estimated biomass increase. Extremely high rates (4.1 and 7.3 Mg·ha⁻¹·yr⁻¹, respectively) were estimated for plots in the Ecuadorian Amazon (Sites 12 and 13) that were measured without ladders. Although the teams attempted to get above buttresses and other stem problems, the nonstandard methods they used included climbing on buttresses and standing on someone's shoulders (J. Korning, *personal communication*). For trees with irregularities extending above breast height, it would seem difficult to obtain accurate measurements with these techniques. While it is impossible to misalign a diameter tape so as to undermeasure a tree, it is easy to overmeasure with a poorly aligned tape and/or one that inadvertently passes over lianas or other objects on the bole (Sheil 1995; D. A. Clark, *personal observation*). Such diameter overestimates, if repeated on a tree at the beginning and end of census intervals, will lead to overestimates of biomass increase, because the same radial increment translates into greater basal area (BA) (and thus biomass) increments on trees of larger diameter. Excluding these two non-ladder plots leaves a data set of 25 sites where trees were measured above buttresses with standard techniques, and where stands were not on young floodplains. This large group of plots (Fig. 1: "Above buttresses") indicates little biomass increase in the humid lowland Neotropics. Mean estimated biomass change is 0.3 Mg·ha⁻¹·yr⁻¹ (95% confidence interval: -0.3 to +0.9 Mg·ha⁻¹·yr⁻¹).

Although this value is not statistically distinguishable from 0, substantially more than half the plots (18 of 25; Binomial test, $P < 0.05$) did show an estimated increase. While this might be evidence of a real trend of biomass accumulation in the lowland humid Neotropics, the summed effects of multiple methods artifacts could have produced the same result. These artifacts could have affected the data from many of these plots. First, there is the upgrowth of bole irregularities over time. When remeasurements are carried out at multi-year intervals, as in most plots in this study, for many trees a measurement site that was originally above buttresses can become affected by them by the time of remeasurement, thus inflating the estimates of growth and of final stand basal area. Second, when tree remeasurements indicate negative increments, some investigators replace these with increments of 0. In tropical forest inventories, diameters are usually measured with an error of ± 1 mm. For those trees that did not grow during a census interval, roughly half their increments will be measured as negative, and half as positive; discarding the "false negatives" and keeping the "false positives" will artificially increase the gain

in stand biomass, as will discarding any true diameter losses (see Clark and Clark 1999). Third, when measurements are at the height of the marker nail (as at Sites 21 and 22; Gentry and Terborgh 1990), they are affected by artificial diameter increases caused by reaction wood developing around the nail. The summed effects of such methods issues may explain the predominantly positive biomass changes estimated for these plots.

CONCLUSIONS

After being screened and reanalyzed, these inventory plot data (Phillips et al. 1998a) do not provide evidence of a substantial biomass carbon sink in old-growth forests of the humid Neotropics. Valuable lessons for future syntheses of such data emerge from this reanalysis. Long-term inventory plots in tropical forests have not been standardized in terms of tree-measurement methods, some of which produce inflated estimates of biomass and biomass change. It is thus critical for analyses of such plot data to be based on a clear understanding of what was done. For historical data sets that are poorly documented, detective work may be called for. When diameter data on field data sheets are accompanied by the measurement heights, and when double measurements are recorded in the same year for some trees because of measurement height changes due to upward-growing irregularities, such evidence indicates trees were measured above bole irregularities (see Sheil 1995, Clark and Clark 2000b). Resolving whether historical data from forest plots were biased by the other problematic measurement protocols will often not be possible, however, because the relevant methods information is rarely published. Finally, for studies focused on old-growth forests, plots on recent floodplains along big river systems should be excluded from analyses unless convincing data indicate they are no longer successional (i.e., evidence of progressively slowing biomass accretion through time, over a decades-long timeline).

The question of whether or not tropical humid forests are accumulating more biomass is important for understanding the global carbon cycle, and it has large geopolitical and economic implications because of carbon sequestration efforts. The available data from old-growth forest plots in the Paleotropics (Phillips et al. 1998a, b) and in the Neotropics (this analysis) do not indicate a substantial biomass carbon sink in tropical humid forests over the last two decades. As seen in this analysis, however, methods of plot measurement have varied across studies, and even the best accepted approaches involve significant uncertainties. Further, the vast majority of tropical forest inventory plots are very small (93% of the 108 lowland Neotropical plots of Phillips et al. [1998a] were ≤ 1 ha, 36% ≤ 0.5 ha). They are also usually subjectively sited and unreplicated. How well they represent processes at the landscape level is open to question (Brown 1997). Many

tropical forest inventory plots have been discontinued. Many types of tropical humid forests have yet to be monitored.

A greatly extended set of long-term plots should be developed around the world tropics. These plots should be replicated within forest landscapes and sited in an unbiased fashion. The measurements should be standardized, highly quality controlled, and much better documented than has been the rule to date. Data from such plots would provide a more robust basis for evaluating the biomass trends in tropical forests.

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