New, Low Estimate for Carbon Stock in Global Forest Vegetation Based on Inventory Data

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Several reports by Intergovernmental Panel on Climate Change (IPCC) have referred to published estimates ranging from 352 to 536 × 10^9 tons for the global pool of carbon in forest vegetation. However, a rounded estimate of 300 × 10^9 tons can be derived from the recent Global Forest Resources Assessment 2000 of the FAO, as shown in this paper. By comparing with independent empirical evidence as published in recent scientific literature and by considering sampling principles and the disturbance cycles of large forest regions, it is argued that the new lower estimate is more realistic. A downward correction of the estimate would make an important contribution to balancing the global carbon budget.

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1 Introduction

Carbon in the Earth system moves between four major reservoirs: fossil and geological formations, the atmosphere, the oceans, and terrestrial ecosystems including forests (Melillo et al. 1993, Siegenthaler and Sarmiento 1993, Prentice et al. 2001, Schimel et al. 2001). Transfers between these reservoirs occur mainly as carbon dioxide (CO_2) in processes such as fuel combustion, chemical dissolution and diffusion, photosynthesis, respiration, decomposition, wild fire, and burning of biomass in the open and in furnaces. If a component of the biosphere such as woody biomass, shrinks, carbon is released into the atmosphere. If biomass expands, it becomes a sink, and thus removes carbon from the atmosphere.

The increasing trend of atmospheric CO_2 (Keeling and Whorf 2002) can partly be attributed to the world´s shrinking biomass. It is important to monitor the carbon stock of the global vegetation. A realistic estimate of the carbon stock at any given time is crucial for two reasons. First, it indicates the potential of vegetation to release or absorb carbon. Secondly, a time series of the carbon stock in vegetation can be used to constrain other methods such as inverse modeling in estimating the net carbon flux to or from the global soils (e.g. Goodale et al. 2002).

The majority of the global vegetation biomass is located in forests (Klein Goldewijk 2001). The focus of this paper is on the contemporary stocks of carbon in forest vegetation, as estimated using forest inventory methodology (Kauppi et al. 1992, Dixon et al. 1994, Goodale et al. 2002, Liski et al. 2003). The FAO published data from such inventories worldwide in October 2001 in *Global Forest Resources Assessment 2000*, here abbreviated as FRA 2000 (FAO 2001). The field work was carried out mainly in the 1990s. FRA 2000 can be used to revisit the estimates derived from FRA 1990 (FAO 1995), an earlier similar study, and can be regarded as a benchmark for estimating the stocks of carbon in the global forest vegetation.

Estimates for the carbon stocks in the global forest vegetation have tended to decrease over time, from 825 Pg (Whittaker and Likens 1973) to the current range of 352–536 Pg (e.g. Olson et al. 1983, Dixon et al. 1994, Houghton 1996, Brown 1998). This range of estimates can be considered as the state-of-art of today, having been referred to in the recent assessments of the IPCC (Bolin et al. 2000, Prentice et al. 2001, Gitay et al. 2001, Kauppi et al. 2001), despite indication in Prentice at al. (2001) that the highest estimate 536 Pg (from Saugier et al. 2001) is probably too high. The aim of this paper is to prepare a new best estimate for the carbon stock of the woody vegetation in the forests of the world based on observations published in FRA 2000, and to judge based on this information and other recent material whether the range of estimates as referred to in the IPCC reports, although lower than previous figures, is still significantly too high.

2 Material and Methods

The carbon pool in forest vegetation in a given region at a given time is obtained by multiplying forest area by the carbon density in vegetation biomass as expressed as $kgCm^{-2}$ (e.g. Brown 1996). Biomass density is obtained based on field measurements such as forest inventories. Forest area is also derived from forest inventories.

The rule in forest inventory is to locate measurements at random or systematically in a statistically sound way so that the sample represents all types of forest, including immature and disturbed stands, and also locations that are temporarily treeless after logging, severe fire, or other disturbances. Even though the accuracy of an estimate obtained in this way will vary according to the inventory design, an appropriately designed inventory is unbiased. In this respect, the inventory methodology is superior to other experimental approaches where bias has been shown towards mature forests thus overestimating the biomass (Botkin and Simpson 1990). It is important to distinguish between inventory and non-inventory methods in estimating the carbon stocks in forests of any large regions.

FRA 2000 is a compilation of national inventories. It refers to ´forest´ as canopy coverage of more than 10% (FAO 2001). It is unclear whether areas that have been temporarily disturbed to canopy coverage less than 10% are included in all national inventories. This conceptual uncertainty does not have much impact on the results of this analysis because forest biomass is concentrated into areas where canopy coverage is equal to or larger than 10%.

The global forests cover 3870 million ha according to FRA 2000 and contain a total standing volume of 386 billion cubic meters of wood. In terms of the mass of the woody vegetation the stock is estimated at 422 billion tons dry matter in the biomass above-ground including stems, branches, tops and foliage (FAO 2001). The average standing stock is thus estimated at 10.9 kilograms per square meter in terms of dry biomass. This corresponds to a carbon pool of 5.45 $kgCm^{-2}$ assuming half of the dry biomass is carbon (Nurmi 1993, Bolin et al. 2000, Prentice et al. 2001). A ratio of 1.22 has been estimated between total and above stump pools in non-tropical regions from FRA 2000 data (Liski and Kauppi 2000). In the tropics, the ratio can vary in the range of 1.1 to 1.5 between regions (Brown 1996).

Uncertainty estimates in the inventory methodology can, in principle, be derived from the data measurements by analyzing the variation between data points and taking into account the sample

Table 1. Forest area and biomass estimates: FRA 2000 (Liski and Kauppi 2000, FAO 2001) and Fang et al. (2001); compared with Houghton (1996,1999).

	TROPICAL			NON-TROPICAL			TOTAL		
	Forest area (10^6 ha)	Woody biomass (Pg C)	Biomass per area (kgCm^{-2})	Forest area (10^6 ha)	Woody biomass (Pg C)	Biomass per area (kgCm^{-2})	Forest area (10^6 ha)	Woody biomass (Pg C)	Biomass per area (kgCm^{-2})
A: FRA 2000 and Fang et al. (2001)									
	1871	164 2)	8.8	1998	93 1)	4.7	3869	257	6.6
B: Houghton (1996,1999)									
	2167	288	13.3	2659	223	8.4	4827	510	10.6
Deviations A versus B									
B–A	296	124	4.5	661	130	3.7	958	253	4.0
B÷A	1.16	1.76	1.51	1.33	2.40	1.79	1.25	1.98	1.60

1) 88 PgC excluding China and 4.75 PgC estimated for China (Fang et al. 2001). All forests of China, Australia and the US are included in "non-tropical forest".
2) Tropical pool is estimated as the total (257) minus non-tropical (93) = 164 PgC. All forests of South America and Africa are included in "tropical forest".

size in relation to the total population (Botkin and Simpson 1990, Achard et al. 2002). For example, the collection of the US data used in FRA 2000 has been designed for an accuracy of ±3% per billion cubic meters of wood volume estimate (FAO 2001). An accuracy of ±10% has been attached to the carbon pool estimate at regional level within Finland (Kauppi et al. 1997). In general, forest inventories have been designed to give quite accurate estimates for commercially important variables like wood volume especially in areas such as Europe and North America, where timber has a high economic value. A likely range of 90.57% to 132.06% has been reported for the best estimate (100%) of total above stump biomass, see Liski and Kauppi (2000) p. 37–39. Estimating below stump biomass and converting volume to carbon introduces error. However, errors in national studies may occur in both directions partly canceling one another in the global estimate. Therefore, a range of 91–132% is here adopted to represent uncertainty of C in the whole-tree biomass of forest vegetation in comparison to the best midrange estimate (100%) as derived from FRA 2000 data.

3 Results

Using the ratio 1.22 for total to above ground biomass, both in non-tropics and tropics, a density for the carbon stock in whole-tree biomass was estimated at $5.45 \times 1.22 = 6.6$ kgCm^{-2}. Applied to the area of 3870 million ha this average stock yields the total carbon stock of 257 Pg as the best estimate. According to FRA 2000, 257 Pg is the most accurate, but still uncertain estimate for the global pool of carbon in woody vegetation in forests in 2000. This estimate is smaller than recent comparable estimates of 356 or 510 Pg, respectively (Dixon et al. 1994, Houghton 1999). These two estimates are important ones, because they were published in the 1990s and have been used by the IPCC when calculating the global carbon budget.

The downward revision is partly a result of FRA 2000´s low estimate for the forest area: at 3870 million ha the FRA figure is 7% and 20% lower, respectively, than in the earlier reports (Dixon et al. 1994, Houghton 1999). The reasons for such large deviations of the area estimate are unclear. The main reason for the revision, however, is the low estimate for the global average biomass density: 6.6 kgCm^{-2} rather than 8.6 (Dixon et al. 1994) and 10.6 (Houghton 1999), respectively.

The uncertainty range between 91% (=233 Pg) and 132% (=339 Pg) suggests that, although the estimate can be considered unbiased, the accuracy is not high, given the variation of research capacity and methods between countries. Using a resolution of one digit for expressing the estimate, 200 Pg is too low to be realistic, 400 Pg is too high; hence, a stock estimate of 300 Pg is reasonable. An estimate as high as 500 Pg can be ruled out. The estimate 300 Pg can be used as the new state-of-the-art, noting that the revision is conservative, the new estimate being on the high side of the mid-range of 257 Pg. If a range of estimates is preferred rather than one number, the new data suggest a range of 233–339 Pg instead of 352–536 Pg as referred to by the IPCC (Bolin et al. 2000, Prentice et al. 2001, Gitay et al. 2001, Kauppi et al. 2001). The two ranges do not overlap.

The new results deviate from those of Houghton (1996, 1999) both for tropical and non-tropical regions (Table 1). The deviation in biomass per area is largest in the tropics in absolute terms. However, in relative terms the deviation is largest in non-tropical regions.

4 Discussion

Literature reviews by the IPCC have estimated the stock of carbon in the global forest vegetation too high. Achard et al. (2002) suggest uncertainty for forest carbon estimates of between ±30% and ±60%. The low end of –60% cannot apply to the data shown in this study, as it would suggest a global pool of only 103 Pg. For non-tropical regions alone, 93 Pg is estimated here (Table 1), and 97 Pg by Goodale et al. (2002). Only 7 to 10 Pg would hence remain for tropical vegetation, which is far too little suggesting the low end of the uncertainty range (–60%) can be ruled out. The high end of +60% would correspond to 411 Pg. Although extremely high as assessed from FRA 2000, this would still be about 100 Pg lower than non-inventory estimates (e.g. Houghton 1996, 1999); yet, higher than 359 Pg (Dixon et al. 1994). Even the lowest end of the IPCC range (352 Pg) is higher than +30% over 257 Pg, and appears to be too high.

The suggestion that the new rounded estimate of 300 Pg is realistic is based on the following arguments:

1) The number of field site actually visited and measured when collecting the data for FRA 2000 can be counted in millions. For example, the global data set of Olson et al. (1983) is based observations from less than 10 000 forest stands. Hence the empirical material of FRA 2000 is about three orders of magnitude larger than has been in use in non-inventory research.
2) The field sites in FRA 2000 methodology are selected to represent all types of forest land, including disturbed land areas resulting from forest fire, cutting, etc., and immature forest stands, while it has been shown for the boreal region and discussed for the tropics that mature stands are over-represented in non-inventory research (Botkin and Simpson 1990, Brown 1996). Therefore, the FRA 2000 observations are not only more numerous, but also qualitatively more appropriate for estimating the carbon stock than are the empirical observations used in non-inventory research.
3) The carbon pool of large forest landscapes, which consists of a mosaic of mature and immature stands and open land, is about half of that in mature stands in both managed and natural forests, especially in non-tropical regions where disturbances have covered large areas (Cooper 1983, Botkin and Simpson 1990).
4) The relative deviation (biomass per area) between FRA 2000 and non-inventory estimates is largest in non-tropical areas where disturbances are more common than in the tropics (Table 1).
5) FRA 2000 data suggest revisions also for non-tropical developed countries where published versions of national inventories are available for comparisons, and the latest research technologies such as remote sensing are available and can be used with ample data measured on the ground (Myneni et al. 2001).
6) FRA 2000 was made available in October 2001, and is based on recent data which were not yet available in the 1990s, nor when writing Bolin et al. (2000), Prentice et al. (2001), Gitay et al. (2001), or Kauppi et al. (2001).

These arguments leave no doubt that many early estimates for the carbon stocks in the global forest biomass have been too high.

A comparison of the new suggested estimate of 300 Pg is particularly interesting with the estimate 359 Pg in Dixon et al. (1994), where the same inventory methodology was applied, but older data mainly from FRA 1990 were used. Data became publicly available from Russia in the 1990s upon release of classified data from the Soviet period. An average carbon density of 3.6 or 5.4 $kgCm^{-2}$, respectively, was reported (Alexeyev et al. 1995, Shvidenko et al. 2000). Consistently, FRA 2000 suggests 4.5 $kgCm^{-2}$

for Russia. In comparison, 8.3 kgCm^{-2} was reported earlier (Dixon et al. 1994). This correction contributes about 34 Pg – more than half – to the suggested revision of the global estimate from 359 to 300 Pg. When estimates for Russia are corrected in this way, the data are consistent for similar ecological areas in Canada, for which a considerable difference existed in earlier data (Dixon et al. 1994).

A smaller part of the revision can be explained by taking into account the real loss of biomass between the measurements of FRA 1990 and FRA 2000. Losses occurred in the tropics while gains were been reported in non-tropical regions (Schimel et al. 2001, FRA 2000, Achard et al. 2002, Liski et al. 2003). Net global losses of 0.2–1.0 Pg annually would have contributed a cumulative loss of 1.6 to 8.0 Pg in approximately eight years that elapsed between taking the measurements for FRA 2000 (this paper) and FRA 1990 (Dixon et al. 1994). The remaining part of the revision can be a result of changing, probably improving practices in inventory methodology. Further research on uncertainties is important.

The woody biomass of forests is estimated in this paper to contain 300 × 10^9 tons carbon. For comparison, the cumulative emissions from the combustion of fossil fuels in the 19th and 20th century were about 280 × 10^9 tons. In 2000, the atmosphere contained about 790 × 10^9 tons in CO_2 (Enting et al. 2001, Marland et al. 2002).

The new finding of this paper is very important for estimating historical long-term budget of carbon in the atmosphere, and for balancing the global carbon budget. Houghton (1996, 1999) suggested that between 1850 and 1990 the vegetation stocks decreased by 79 PgC in tropical forests and by 45 PgC in non-tropical forests; thus a loss of 124 Pg from forests triggering gains in the atmosphere. A loss of 124 Pg from an initial 601 Pg in 1850 (Houghton 1996) is a loss of 20.6%. A loss of 20.6% from a lower initial biomass would imply a loss of *only 62 Pg* from forest biomass into the atmosphere (notably from 362 to the current 300 Pg). This reasoning is indicative because Houghton included all lands not just forests, and there are other differences in the methods as well. Although the loss of forest vegetation has not been insignificant the combustion of fossil fuels may have driven the change of the atmosphere even more strongly than hitherto estimated.

Siegenthaler and Sarmiento (1993) after not finding a satisfactory balance of the global carbon budget concluded that: "*either the emission estimates are significantly too high or there is a sink not accounted in this balance*". It is possible that forest emissions have been estimated too high as a consequence of overestimating the initial carbon stock. The "missing sink" as frequently discussed in the literature in the 1980s and 1990s can partly have been a result of artifacts, overestimating the lost forest area and/or the carbon density of forest vegetation and thus overestimating the historical net emissions of carbon dioxide from the forests of the world.

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