
Forest Harvests and Wood Products: Sources and Sinks of Atmospheric Carbon Dioxide

Jack K. Winjum, Sandra Brown, and Bernhard Schlamadinger

ABSTRACT. Changes in the net carbon (C) sink-source balance related to a country's forest harvesting and use of wood products is an important component in making country-level inventories of greenhouse gas emissions, a current activity within many signatory nations to the UN Framework Convention on Climate Change. We propose two approaches for estimating national C inventories from forest harvesting and wood product utilization (excluding forest regrowth): the atmospheric-flow method and the stock-change method. The former has the atmosphere as its system of interest and counts all flows to and from the atmosphere for a particular country. The latter looks at a country's forest and wood product C stocks and how they change over time. Here we develop these two methods, and estimate national C source-sink balance from the readily available FAO global forest products database for countries, regions, and the world. Both methods gave a worldwide estimated source of 980 Tg of C in 1990 as a result of forest harvests and wood product utilization; about 60% came from developing countries and 40% from developed countries. Estimates (Tg C) for selected developing countries for the atmospheric-flow/stock-change method were: Brazil, 72/73; India, 81/80; Indonesia, 53/56; and Ivory Coast, 3.9/4.3; and for selected developed countries (again atmospheric-flow/stock-change method): Canada, 36/50; Finland, 8.8/13; New Zealand, 2.7/3.4; and United States 141/138. Net wood exporters show lower numbers in the atmospheric-flow method, net wood importers in the stock-change method. Among the variables that most consistently and strongly affected C emissions for a given country in 1990 were: roundwood production, slash left to oxidize, and commodity wood put into uses ≥ 5 yr. We conclude with a discussion that shows how choosing either one of the two methods for wood harvest accounting has potential policy implications or impacts on the incentives or disincentives to use wood. *FOR. SCI.* 44(2):272–284.

Additional Key Words: Carbon balance, commodities, fuelwood, greenhouse gas inventory, roundwood, atmospheric-flow method, stock-change method.

FOREST HARVESTING FOR WOOD PRODUCTS alters the natural cycle of carbon (C) between forest ecosystems and the atmosphere. On a country scale, harvesting may significantly change the net C sink-source balance related to a country's forest resources and wood utilization. The balance is an important component in country-level C budget analyses, a current activity within many signatory

nations to the UN Framework Convention on Climate Change (UN FCCC) (Dixon et al. 1996).

In the early 1990s, investigators undertaking forest C budgets began considering the effects of harvesting and utilization of wood products. To expedite development, early analyses used simple modeling or spreadsheet approaches with many simplifying assumptions (e.g., IPCC 1995, Subak

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et al. 1993). In addition to these simple approaches, several country-level C budgets for the forest sector have been estimated that have included forest harvesting for wood products, including Canada (Kurz et al. 1992), Finland (Karjalainen et al. 1994), Germany (Burschel et al. 1993), the United States (Heath et al. 1996, Row and Phelps 1996), and the U.S. Pacific Northwest (Harmon et al. 1996). In addition to country-level C budgets, stand-level analyses that incorporated an accounting for C sequestration in wood products produced from harvests of managed forests representing major forested regions of the world have also been developed (Nabuurs and Mohren 1995).

Although these studies all included estimates of the transfers of C in wood utilization for wood products, methods of accounting varied by country. For example, some included imports and exports of roundwood or commodities; others did not. Others tracked the transfers of C in products into long-term storage and their subsequent decay rates, and one estimated the increase in long-term wood C storage based on the increase in residence structures and their corresponding wood content.

All of the above studies estimated C sources and sinks of forest harvesting and wood products for specific purposes and locations. They also made advances in addressing key C pathways, transition rates, and changes during past and future decades. Furthermore, these previous studies suggest that there are two basic approaches for accounting for C sources and sinks from forest harvesting depending on the frame of reference that one considers. One approach considers the frame of reference to be the atmosphere, and it accounts for the effects of forest harvesting and wood trading on all C fluxes to and from the atmosphere for a particular nation; we refer to this as the atmospheric-flow method. It is generally similar to the procedure for accounting for emissions from fossil fuel systems described in the IPCC (1995). However, the atmospheric-flow method is fundamentally different from the IPCC 1995 method for accounting for emissions from the harvesting and use of wood. Even if countries had no change in wood product stocks (an assumption implicitly made in the IPCC 1995 method), the results would be different between the atmospheric-flow method and the IPCC 1995 method because the latter has its system boundary around a country's forest and calculates the change in the forest C stock.

The second approach considers the frame of reference to be a closed system boundary around a country. This approach accounts for changes in the storage of C on forestlands and in long-term wood products pools; we refer to this as the "stock-change method." This method is similar to the current IPCC (1995) method for accounting for wood harvesting. The IPCC 1995 method calculates the flux out of the forest C stock in two main steps: roundwood consumption plus slash emissions. In the case of a constant forest C stock, this flux would be exactly balanced by C uptake during forest regrowth. The stock-change method also considers a possible change (decrease or increase) in C stocks of long-term wood products per country. For countries with no change in wood product stocks, the IPCC 1995

method and the stock-change method would yield identical results. Given that in most countries wood product stocks are probably increasing, the stock-change method will yield a greater net C sink (or a smaller net C source given a declining forest stock) than the IPCC 1995 method.

The goals of the research reported in this paper were to: (1) develop the methodology for the two approaches described above, (2) apply these methodologies to the FAO (1995) database of wood products to estimate the global C source-sink balance from forest harvesting and wood utilization, (3) determine what differences occur in the C balance between the two methods and how the differences vary by developed and developing countries, and (4) discuss the policy implications of the two methods for national greenhouse gas emission inventories for compliance with the UN FCCC.

Methods

The general equation for the atmospheric-flow method is: net C flux to atmosphere = C fluxes to the atmosphere associated with harvesting and use of wood - C uptake during regrowth of harvested forests.

The C fluxes associated with harvesting and use of wood include: C emissions from (1) decomposition of slash left in the forest after harvesting, (2) burning of fuelwood and charcoal, (3) waste produced from the conversion of roundwood into commodities, (4) decay of long-term wood product pool, and (5) commodities going into short-term use with an assumed immediate oxidation (Figure 1).

The general equation for the stock-change method is: net change in C storage equals net change in the C stock of forests due to harvesting and regrowth plus net change in the long-term wood product pool. The net change in the forest C stock is the difference between C accumulation by regrowth and the amount of wood harvested and the decomposition of the resulting wood slash. The change in the long-term product pool is the difference between production of long-term wood commodities and inherited emissions from past wood usage. The details of how all these terms for both approaches are calculated are given below.

Both approaches include the forest regrowth term. This is basically a simple calculation of area of regrowing forests times rate of regrowth for different forest types and age classes. In practice, however, there is no consistent and reliable database to make these calculations in a reliable manner for most countries of the world, particularly the developing countries. Therefore, the uptake of CO₂-C by forest growth is not included here in the global analysis, although a few examples for which data are generally reliable will be included for comparison. The development of a consistent database of forest regrowth is a vital need to calculate the net C balance of the world's forests.

Input Data

We used the FAO forest products data (FAO 1995) with both the atmospheric-flow and stock-change method to estimate the influence of wood harvesting on a nation's C source-sink balance. This database, spanning more than 30 yr, is an internationally recognized source of forest products data. In

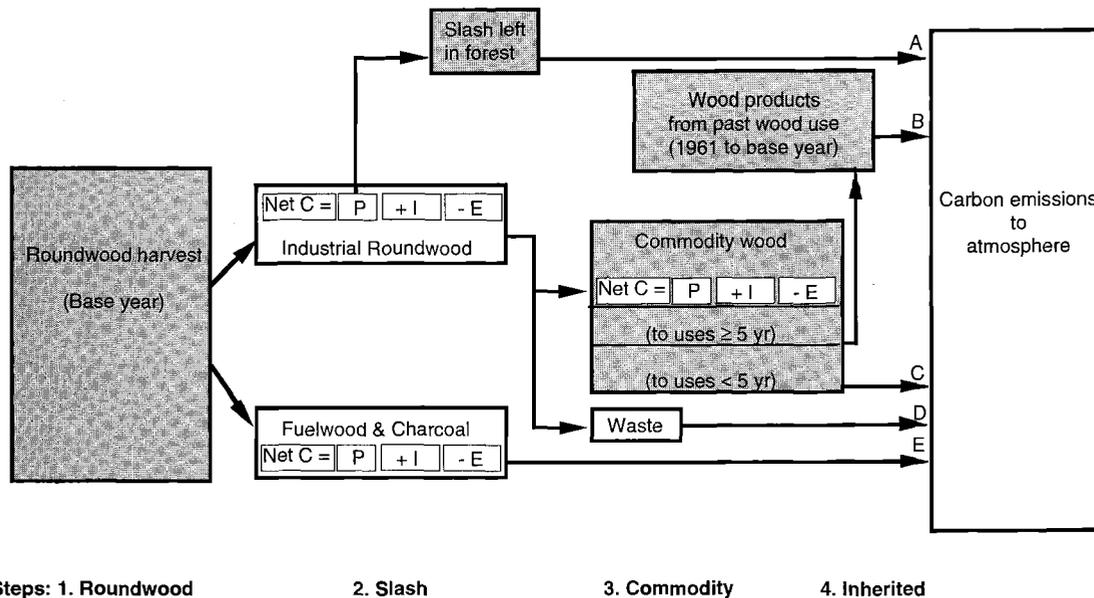


Figure 1. Diagram of steps used in the atmospheric-flow method for computing estimates of a country's annual carbon emissions to the atmosphere from forest harvests and use of wood products. C = consumption, P = production, I = imports, and E = exports. The arrows to the box labeled carbon emissions to the atmosphere represent the C fluxes due to A—decomposition of slash, B—oxidation or decay of long-term wood products (≥ 5 yr) from past use (inherited emissions), C—oxidation of wood products with short-term (< 5 yr) uses, D—oxidation of waste (burning or decaying) from the production of commodities, and F—burning of fuelwood and charcoal. The shaded boxes are those used in calculations for the stock-change method.

electronic form, it currently spans the period 1961 through 1993 and is updated annually. The year 1990 became the base year for the analyses for this paper to be consistent with related C analyses of global forests (Dixon et al. 1994, Schimel et al. 1995).

Definitions of terminology of wood products used in the FAO's database (FAO 1995) were adopted for the methodology. For annual harvests, we selected the annual production numbers for two FAO categories: industrial roundwood (logs) and fuelwood plus charcoal; the sum of these two categories is referred to by the FAO as roundwood. Annual wood products production was represented by four commodity categories: sawnwood (dimension lumber, etc.), woodbase panels (plywood, decorative panels, etc.), other industrial roundwood (i.e., poles, pilings, fence posts, etc.), and paper and paperboard.

Conversion Factors

Because the FAO database reports most quantities in volume units, several conversion factors are required to express harvested wood in terms of dry mass before oxidation. The FAO data for roundwood are inside-bark volume; thus a bark fraction must be added to estimate the total volume removed from the forest. We used an average bark fraction of 0.11 for conifers, 0.13 for nonconifers, and a mean of 0.12 for aggregated roundwood harvests (Haygreen and Bowyer 1989).

Further, as harvests of roundwood and most commodity wood in the FAO database are in green log volumes, i.e., thousands of cubic meters (m^3), a conversion to dry mass [Mg (10^6 g) of dry matter] was required. For this purpose, biomass conversion factors were developed (Table 1) representing mean wood densities of conifer and nonconifer stemwood at oven-dry weight for green volumes (Mg/m^3) (USDA 1987).

Average conversion factors were determined for the boreal, temperate, and tropical forest regions on the basis of densities for common regional tree species (Chudnoff 1984, Reyes et al. 1992, USDA 1987). In like manner, biomass conversion factors for commodities (Table 1) were developed from FAO (1995) tables. To convert the dry mass of wood in roundwood and commodities to C contents, we used the common fraction of 0.5 (Brown 1997), which, for our estimating purpose, adequately represented a reported narrow range of 0.48 to 0.53 (Birdsey 1992). The annual estimates of C emissions were reported in teragrams of C ($Tg\ C = 10^{12}$ g C).

Tree Species

The methodology used data for three categories of tree species: "Conifer, NonConifer" and "Aggregate." Which category we used in our analyses was determined by the level of breakdown in the FAO database with regard to production, imports, and exports for each roundwood or commodity category. Tables in FAO (1995) vary in this regard.

Atmospheric-Flow Method

We grouped calculations for the atmospheric-flow methodology into four main steps: roundwood (industrial and fuelwood and charcoal) consumption, slash emissions, commodity consumption, and inherited emissions (Figure 1), these steps result in one or more of the C fluxes to the atmosphere associated with forest harvest and wood products. The final estimate of total emissions to the atmosphere is a simple addition of the end results of the four steps, that is, the sum of emissions from: decomposition of slash (A), decay and oxidation of the long-term wood products pool (uses ≥ 5 yr) (B), decay and oxidation of short-term wood products (uses < 5 yr) (C), oxidation of waste produced in the conversion of industrial roundwood to commodities (D), and burning fuelwood and charcoal (F).

Table 1. Biomass conversion factors (Mg m^{-3} green volume) by region and species group used to compute roundwood and commodity biomass from volumes reported in m^3 by region.

Region/spp group	Roundwood*		Commodities†		
	Industrial (1)	Fuelwood (2)	Sawnwood (3)	Woodbase panels (4)	Other industrial roundwood (5)
Boreal					
Conifer	0.40		0.42		0.56
Nonconifer	0.45		0.47		0.64
Aggregate	0.42	0.42	0.44	0.52	0.60
Temperate					
Conifer	0.40		0.42		0.56
Nonconifer	0.50		0.53		0.64
Aggregate	0.45	0.45	0.48	0.52	0.60
Tropical					
Conifer	0.50		0.53		0.60
Nonconifer	0.60		0.63		0.70
Aggregate	0.55	0.55	0.58	0.62	0.65

* Biomass conversion factors adapted from Chudnoff 1984, Reyes et al. 1992, and USDA Forest Service 1987.

† Volume to mass relationships for wood commodities adapted from FAO (1995).

Step 1. Roundwood Consumption

For the base year of 1990, net biomass consumption was calculated for industrial roundwood and fuelwood and charcoal (F in Figure 1). Using FAO (1995) data, industrial roundwood consumption was calculated separately for conifer and nonconifer and then summed. For fuelwood and charcoal, species data were aggregated before calculations because FAO data on imports and exports were not separated by species groups. Consumption of wood biomass was calculated in three steps: (1) net annual consumption equaled production (P , i.e., harvests) plus imports (I) minus exports (E) all in m^3 (Figure 1); (2) total volume required an addition for bark volume (see above); and (3) conversion of volume to dry weight by a biomass conversion factor (Table 1).

The charcoal portion of the roundwood consumption calculations was treated somewhat differently. The FAO (1995) data on charcoal are in units of dry mass, but when aggregated with fuelwood, the FAO converts charcoal dry mass to wood volume equivalents (m^3). We used the data expressed as dry mass of charcoal because we were interested in the CO_2 -C emissions only and not the CH_4 and CO emissions produced in the conversion of wood to charcoal, which are not included in this analysis. Further, as practically all the wood harvested for charcoal is used in manufacturing the charcoal, particularly in developing countries where most charcoal is consumed, we made two assumptions: (1) no significant amounts of slash were produced from forest harvests for charcoal and (2) the burning of charcoal, with a C-content fraction of 0.7 (IPCC 1995), emits only CO_2 -C. We estimated net consumption as production plus imports minus exports, the same as for industrial roundwood and fuelwood.

Step 2. Slash

We assumed that after industrial roundwood harvests, on-site slash (leaves, twigs, branches, tops, and stumps) oxidizes (i.e., decomposes or burns) in the base year as is done in the current IPCC (1995) methods (A in Figure 1). Slash biomass was estimated by first calculating the preharvest biomass in the forest from data on industrial roundwood production. The calculation was based on biomass expansion factors (BEF)

adapted from the literature, i.e., factors that convert commercial wood biomass in forests to total biomass, including noncommercial components (i.e., BEF = total aboveground biomass divided by commercial wood biomass). Factors used were 1.3 for conifers (Brown 1997) and 2.0 for nonconifer forests (Brown and Lugo 1992, Schroeder et al. 1997).

We assumed that the 2.0 factor applies to nonconifer forests of both temperate and tropical regions for the following reasons. For a forest containing a given inventoried volume, tropical forests contain more total aboveground biomass than a temperate forest; that is, the BEFs for tropical forests are higher than those for temperate forests (Schroeder et al. 1997). Further, BEFs decrease with increasing amounts of inventoried volume (Brown and Lugo 1992, Schroeder et al. 1997). However, harvesting in the tropics commonly occurs in mature forests with high volumes (FAO 1993) whereas harvesting in temperate nonconifer forests commonly occurs in less-than-mature forests, with lower volumes (Birdsey 1992). Thus, the expansion factors for forests in both zones tended to be similar to each other.

The BEFs times a mean wood density factor (to convert volume to mass; 0.43 and 0.52 $\text{Mg dry matter m}^{-3}$ for conifers and nonconifers, respectively), gave factors of 0.56 and 1.04 $\text{Mg total biomass m}^{-3}$ roundwood for each species group. The product of these factors and the industrial roundwood production volumes provided an estimate of the total aboveground biomass of forests prior to harvesting. Subtracting the industrial roundwood production (converted from volume to mass) gave an estimate of postharvest slash.

Significant amounts of biomass may be removed annually from forests as fuelwood, both on a formal and informal basis. Removals are from existing forests or from slash after harvests, either before regeneration of new stands or before conversion to other land uses. Fuelwood production estimates given in the FAO Forest Products Yearbook (1995) are, in general, a combined value of both formal and informal fuelwood harvests. For most developing countries, fuelwood and charcoal estimates presented by FAO (1995) are based on per capita consumption and population density.

To prevent the problem of double counting emissions from postharvest slash, it was critical that a reasonable estimate be made of the fraction of slash removed for fuelwood and charcoal. The fraction was deducted from the total postharvest slash in the final accounting. As actual data on such usage are generally lacking, we assumed that these fractions were 0.75 for developing countries (i.e., high demand for fuelwood and charcoal) and 0.125 for developed countries. If reported fuelwood and charcoal usage for a given country was less than the product of postharvest slash and the multiplier fractions, we deducted the actual reported fuel needs from the postharvest slash.

Step 3. Commodity Wood

Wood products put into uses lasting 5 yr or more were considered long-term uses. Long-term uses of wood were calculated for four commodity groups given in the FAO database: sawnwood, other industrial roundwood, woodbase panels, and paper and paperboard. Not all wood commodities produced go to uses or into storage for 5 yr or more—only a portion; the remainder (short-term use < 5 yr) was assumed to be oxidized in the base year. The proportions that go into long-term products were estimated to be: sawnwood, 0.8; woodbase panels, 0.9; other industrial roundwood, 0.7; and paper and paperboard, 0.6 (derived from Kurz et al. 1992, Nabuurs and Mohren 1993, Row and Phelps 1996). We assumed, based on these sources, that approximately 20% of the paper and paperboard produced was utilized in end-uses with services \geq 5 yr, and of the remaining 80%, half (another 40%) was landfilled for periods \geq 5 yr.

The FAO database reports: (1) volumes (m^3) for sawnwood and other industrial roundwood by the conifer and nonconifer categories; (2) volumes (m^3) for woodbase panels aggregated by species; and (3) dry mass (metric tons or Mg) for paper and paperboard aggregated by species. For each commodity/species category, we first calculated net annual consumption (in m^3 or Mg) as: production plus imports minus exports (Figure 1). Net consumption of sawnwood, other industrial roundwood, and woodbase panels was multiplied by: (a) the fraction in uses \geq 5 yr (above); and (b) the biomass conversion factor (Table 1). For paper and paperboard, net consumption was multiplied only by the fraction 0.6. All categories were finally summarized to estimate the total net biomass assigned to uses \geq 5 yr out of the wood harvested or imported in the base year.

The proportion of commodity wood that goes into short-term products (C in Figure 1) was calculated as the difference

between the total net consumption of each commodity group and the amount that went into long-term products.

When industrial roundwood is processed into wood commodities, some wood is lost as waste (D in Figure 1) because conversion efficiencies into commodities are less than 100%. We assumed that the waste was oxidized in the base year, though we recognize that some might be made into wood commodities with a small portion of that put into uses or landfills for periods \geq 5 yr. We calculated C emissions from wood waste as the difference between the C in industrial roundwood consumed and the C in wood commodities produced (Figure 1).

Step 4. Inherited Emissions

During any year, C emissions emanate from the oxidation (i.e., burning and decay) of long-term wood products that were produced from harvests during previous years. These emissions, termed inherited emissions, were attributed to the current base year. For simplicity, we made two assumptions in estimating inherited emissions:

1. Using the FAO database, the amount of wood (and therefore C) remaining in service from the use of commodities prior to 1961 (the earliest year in the database) is likely a low value for most countries, and therefore, was not included. The assumption was mostly driven by the fact that there were limited data on existing pre-1961 wooden structures for countries worldwide. However, this assumption is supported by other data such as world populations prior to 1961 that were smaller than at present. For instance, world populations in 1950 and 1960 were 47% and 57%, respectively, of the 1990 population of 5.3 billion people (United Nations 1994). Though some wooden structures remain in service up to a century or more (Kurz et al. 1992, Row and Phelps 1996), the amount of wood contained in such uses (and the current C emissions therefrom) that were associated with the low human populations before 1961 was assumed to be negligible. This is particularly true for developing countries where production and consumption of wood for long-term wood uses has historically been low (Laarman and Sedjo 1992).
2. Wood in long-term use was retired at a constant annual rate over time (Table 2). Though several authors have presented nonlinear trends (Kurz et al. 1992, Row and Phelps 1996), we used simple straight-line relationships based on commodity groups and major latitudinal regions. The relationships are repre-

Table 2. Annual oxidation fractions (yr^{-1}) of in-use wood commodities that decay or burn each year within the three major forest regions of the world.*

Commodity	Forest region		
	Boreal (1)	Temperate (2)	Tropical (3)
Sawnwood	0.005	0.01	0.02
Woodbase panels	0.010	0.02	0.04
Other industrial roundwood	0.020	0.04	0.08
Paper & paperboard	0.005	0.01	0.10

* Adapted from Dewar 1990, Harmon et al. 1995, Karjalainen et al. 1995, Kurz et al. 1992, Nabuurs and Mohren 1995, and Row and Phelps 1990.

sented by annual oxidation fractions or the amount of in-use wood commodities that decay or burn each year (Table 2). Also to keep complexity to a minimum, the methodology does not distinguish between wood that was retired and immediately burned, recycled, or that was retired and put into landfills. For the United States in 1990, Heath et al. (1996) reported that wood depositions into landfills accounted for 16 Tg C. However, landfill deposition data for wood were not found in global databases covering the countries of the world; therefore, emissions from this source were not distinguished from inherited emissions of C through retirement of wood in use.

Using FAO data for each year from 1961 through 1990, calculations of net consumption were completed for the same commodity/species categories as for commodities in Step 3. Resulting net consumption values were also multiplied by the fraction in uses ≥ 5 yr, by the biomass conversion factor, and by the appropriate annual oxidation fraction of in-use wood commodities that decay or burn each year (Table 2). The sum of the 30 yr of annual biomass retirements for all commodity/species categories gave the inherited biomass released in the base year.

For the oxidation fractions of 0.04, 0.08, and 0.10 (Table 2), the period of oxidation would extend back 25, 12, and 10 yr from the base year, respectively. Therefore, for the years prior to these periods, the fraction was zero as it was assumed that all of the wood commodities used before these periods would have been completely oxidized.

Stock-Change Method

The stock-change method uses a selection of the quantities already estimated above for the atmospheric-flow method (Figure 1). The specific equation for the stock-change method is: net change in C stocks = (C uptake – industrial roundwood production – fuelwood and charcoal production – decomposition of slash) + (commodities to use ≥ 5 yr – inherited emissions). As noted above, we do not consider C uptake by forests, and thus only estimate the flux out of the forest stock. We do, however, consider both the fluxes into and out of the wood product stocks. The sign convention here is somewhat different from the atmospheric-flow method because of the difference in the frame of reference between the two methods. As the frame of reference for the stock-change method is the land rather than the atmosphere, the production of roundwood and decomposition of slash represent losses from the land, thus these terms are preceded by a negative sign.

Application of Methodologies

We applied the two methods to the FAO (1995) data on forest products to estimate the net C source-sink balance for the globe, for developed versus developing country categories, and for eight countries that provided a wide geographical representation among significant forest growers and wood products consumers. Based on category listings by FAO, four

developing countries were selected: Brazil, India, Indonesia, and Ivory Coast. Among developed countries, we included: Canada, Finland, New Zealand, and the United States

Sensitivity Analysis

As noted, each step in the calculations contained one or more conversion factors or fractions for use in the fate of C as a result of annual harvests and wood product use within countries. A sensitivity analysis was conducted for each of these items by increasing them individually 10% and determining the corresponding percent change in the total C emission estimate for the base year. To determine the broad impact of the factors and fractions, the sensitivity analyses were conducted for the two country categories, developing and developed.

Results

Roundwood Harvest

For seven of the eight countries analyzed, the differences between in-country roundwood harvests (i.e., production) and net consumption as a result of imports and exports in 1990 were less than 5% (Table 3). Five countries, Brazil, Canada, Finland, India, and Indonesia, were net importers of roundwood, but by narrow margins. Net exporters included Ivory Coast, New Zealand, and the United States, although also at narrow margins.

Most of the roundwood C consumed in developing countries was for fuelwood and charcoal (79%). However, the proportion varied by country, ranging from 69% for Brazil to 89% for India (Table 3). In contrast, roundwood C consumption was predominantly in industrial roundwood for developed countries. Three of the developed countries used less than 10% of their total roundwood-use as fuelwood and charcoal; the United States was highest at 18%. Worldwide, the portion of the total used as fuelwood and charcoal was 54%.

Of the worldwide 949 Tg C in net roundwood consumed, about 60% was within developing countries (Table 3). Developing countries, however, exported twice as much roundwood as they imported. Developed countries consumed about 40% of the world total roundwood and imported 1.2 times as much roundwood as they exported.

Slash Production

On a global basis, forests that were harvested for industrial roundwood production contained 682 Tg C of original forest biomass (Table 4). Of this original biomass, 64% was harvested for industrial roundwood, 11% was removed for fuelwood and charcoal, and 25% was left as slash. In developing countries, about 9% of the pre-harvest C was estimated to remain on site as slash after harvesting. In contrast, developed countries had about 32% left in slash.

Commodity Wood and Waste

For 1990, we estimated that 252 Tg C representing 74% of the net consumption of wood commodities went into uses that had a life of 5 yr or greater and 94 Tg C into short-term use products (Table 5). There were no differences in how commodities were allocated between short-term and

Table 3. Roundwood consumption and uses by developing and developed countries and the world as a whole in 1990.

Category/ country	Production	Roundwood consumption (Tg C)			Roundwood uses (Tg C)*	
		Import	Export	Net†	IR	F&C
	(1)	(2)	(3)	(4)	(5)	(6)
Developing						
Brazil	73	0.04	0.01	73	23	50
India	82	0.45	0.02	83	9	74
Indonesia	55	0.02	0.01	55	12	43
Ivory Coast	4	0	0.14	4	1	3
Developed						
Canada	40	0.37	0.27	41	39	2
Finland	10	1	0.07	11	10	1
New Zealand	2.7	0.002	0.37	2.3	2.3	0.01
U.S.A.	123	0.08	5	118	97	21
Worldwide						
Developing	583	5	10	579	123	456
Developed	367	16	13	370	311	59
Total	950	21††	23††	949	434	515

* Roundwood uses are: IR, Industrial Roundwood, and F&C, Fuelwood and Charcoal.

† Net consumption = Production + Import - Export; row and column sums are subject to rounding.

†† These two values should equal each other; their difference reflects some inconsistencies in the FAO database.

long-term uses between the developing and developed countries. Of the wood going into long-term use commodities, most was used for sawnwood (38%), followed by paper and paperboard (29%), by other industrial roundwood (20%), and woodbase panels (13%). The same order of use was approximately true for the developing and developed countries. For the developing countries, however, more C was retained in other industrial roundwood (32% of the commodity total) than in paper and paperboard (21%).

Among the countries analyzed, high proportions of C in wood commodities were exported by Canada (65% of production), Finland (71%), Indonesia (43%), and New Zealand (40%) (Table 5). The United States imported 16% of its net consumption. Worldwide, exports and imports balanced, as expected, with each containing 17% of the C within commodity production.

The global production of wood waste from the conversion of industrial roundwood to commodities was estimated to be 88 Tg C, with developed countries producing about twice as much as developing ones (Table 6). Globally, the amount of wood waste accounted for 20% of the industrial roundwood consumed, with developing countries producing slightly more waste than developed countries (24% and 19%, respectively). However, the amount of waste produced as a percent of industrial roundwood consumed varied widely among the individual countries considered here, from 11% to 56% for the four developing countries and from 25% to 51% for the four developed ones.

Inherited Emissions

In 1990, developing countries had 42 Tg C or 37% of the total inherited emissions for the world and developed countries had 71 Tg C or 63% (Table 6). Over the 30 yr period, the inherited emissions for developed countries exceeded those

Table 4. Estimate of net slash left to decompose in 1990 after Industrial Roundwood harvests and after deducting the Fuelwood and Charcoal collected from the harvest site. All units are in Tg C.

Category/ country	Industrial roundwood production*	Preharvest biomass	Postharvest slash†	Fuelwood & charcoal††	Net slash left‡
	(1)	(2)	(3)	(4)	(5)
Developing					
Brazil	23	35	12	9	3
India	9	14	5	4	1
Indonesia	12	21	9	7	2
Ivory Coast	1	2	1	1	0.2
Developed					
Canada	39	56	18	2	15
Finland	9	14	5	1	4
New Zealand	2.7	4	1	0.01	1
U.S.A.	102	165	63	8	55
Worldwide					
Developing	128	199	71	54	18
Developed	308	483	174	22	152
Total	436	682	246	75	170

* The values are for the Industrial Roundwood portion of column 1 in Table 3 (i.e., the in-country production).

† Column (2)—column (1), subject to rounding.

†† The fuelwood and charcoal values here are less than those of Table 3 as they represent only that amount of total production collected from slash (see text for further details).

‡ Column (3)—column (4), subject to rounding.

Table 5. Commodity wood production (P), imports (I), exports (E), net consumption (Net), and amounts allocated to four commodity groups for uses ≥ 5 yr and < 5 yr (Tg C in 1990).

Category/ country	Commodity consumption				SWD	Commodity use ≥ 5 yr [†]			Total	Uses < 5 yr ^{††}
	P	I	E	Net*		WBP	OIR	P&P		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Developing										
Brazil	10	0.2	1	10	4	1	1	1	7	2
India	8	0.1	0.02	8	4	0.1	1	1	6	2
Indonesia	7	0.1	3	4	2	0.1	1	0.42	3	1
Ivory Coast	1	0.02	0.2	0.4	0.05	0.03	0.2	0.01	0.3	0.1
Developed										
Canada	23	1	15	9	3	1	1	2	7	2
Finland	7	0.1	5	2	0.6	0.2	0.1	0.4	1.2	0.5
New Zealand	1	0.1	0.4	0.8	0.3	0.1	0.1	0.2	0.6	0.2
U.S.A.	73	13	6	81	23	8	3	23	57	24
Worldwide										
Developing	93	11	10	94	26	6	22	14	68	26
Developed	253	47	48	252	70	27	29	58	184	68
Total	346	58	58	346	96	33	51	72	252	94

* Net consumption = Columns 1 + 2 - 3.

[†] The four commodity groups are: SWD, Sawnwood; WBP, Woodbase Panels; OIR, Other Industrial Roundwood; and P&P, Paper & Paperboard.

^{††} Uses < 5 yr = Column (4) - Column 9; subject to rounding.

of developing countries for all four commodity groups. Both regions, however, had their highest inherited emissions from consumption of other industrial roundwood; next in order were sawnwood and paper and paperboard. In addition, developed countries had much larger amounts of woodbase panels consumption than did the developing countries.

Among the eight countries, the estimated inherited emissions for the United States of 17 Tg C were over four times as much as those for the next two highest countries of Brazil and India, at 4 and 3 Tg C, respectively (Table 6). The relatively large inherited emissions for the United States result from a 30 yr history of large consumption of, and therefore inherited emissions from, sawnwood, woodbase panels, and paper and paperboard. Brazil's consumption for the period was large for sawnwood, other industrial roundwood, and paper and paperboard.

Total Net Emissions: Atmospheric-flow Versus Stock-Change Methods

Based on the atmospheric-flow method, we estimated that 980 Tg C were emitted in 1990 from forest harvests and past use if wood (Table 6). By category, 58% originated from developing countries and 42% from the developed countries. Of the eight countries analyzed, the United States had the highest 1990 emissions of 141 Tg C or about 14% of the global total (Table 6). India was second with 81 Tg C emissions, and New Zealand was the lowest, 2.7 Tg C.

The global total of 981 Tg C calculated by the stock-change method (Table 7) appears to show a net C loss relative to the land because the C uptake in the forest is not taken into account. However, as expected, the amount is the same as the total emissions from the atmospheric-flow method. The partitioning is also more or less the same

Table 6. Summary of C emissions, estimated by atmospheric-flow method, by categories and countries (in Tg C for 1990).

Category/ country	C emissions					Total
	Slash*	Inherited	Commodity uses < 5 yr [†]	Waste ^{††}	Fuelwood & Charcoal [§]	
Figure 1	A	B	C	D	F	(6)
	(1)	(2)	(3)	(4)	(5)	(6)
Developing						
Brazil	3	4	2	13	50	72
India	1	3	2	1	74	81
Indonesia	2	1	1	5	43	53
Ivory Coast	0.2	0.2	0.1	0.4	3	3.9
Developed						
Canada	15	1	2	16	2	36
Finland	4	0.3	0.5	3	1	8.8
New Zealand	1	0.3	0.2	1.2	0.01	2.7
U.S.A.	55	17	24	24	21	141
Worldwide						
Developing	18	42	26	30	456	572
Developed	152	71	68	58	59	408
Total	170	113	94	88	515	980

* Column 5, Table 4.

[†] Column 10, Table 5.

^{††} Waste = (industrial roundwood consumption, column (5) Table 3) - (commodity production, column (1) Table 5).

[§] Column 6, Table 3.

between developed and developing countries as for the atmospheric-flow method. All countries show an increase in C stocks of long-term wood products (Col. 3 > Col. 4 in Table 7), and the global increase corresponds to about 14% of the global forestry and wood products flux to the atmosphere. However, the increase in C stocks in wood commodities is 28% of the total emissions in developed countries, but only 5% in developing countries.

A comparison of the results from the two methods for the eight individual countries considered here gives different results, particularly for the developed countries. For example, the stock-change method for Canada, Finland, and New Zealand produced estimates that are 130 to 150% higher than the atmospheric-flow method. These three countries export a relatively large proportion of their commodities and industrial roundwood (Table 3 and 5). For the United States, the stock-change and atmospheric-flow method gave practically the same results because imports and exports of industrial roundwood and commodities are generally balanced. The stock-change and atmospheric-flow method for Indonesia and Ivory Coast give estimates that are different by about 10%, once again because these two countries are net exporters of roundwood and commodities.

Sensitivity Analyses

Of the 12 sensitivity analyses conducted, most changes to the estimated C emissions in 1990 were about 2% or less (Figure 2). Of the three analyses that produced the largest changes (>7%), two were for the developed countries: industrial roundwood biomass conversion factor (7.7%); and slash biomass expansion factor (10.4%). The latter change was the highest because 37% of the C emissions for these countries were from slash oxidation (Table 6). The one large change for the developing countries was for the fuelwood and charcoal biomass conversion factor (7.7%), again because 80% of their emissions originate from burning fuelwood and charcoal (Table 6).

Forest harvesting in native tropical forests is most commonly by a selection method with only a few trees/ha removed. However, mortality and damage leading to delayed mortality among the residual live trees can be as much as 20% of the initial standing stock (Pinard and Putz 1996). In this situation, the factor to calculate slash production in these forests may range from 4.0 to 6.0 (Pinard and Putz 1996). To test what effect this damage to the residual stand from poor logging practices may have on C emissions, we conducted a sensitivity analysis for the developing countries using a biomass expansion factor of five. The larger factor raised the amount of slash left to oxidize post-harvest, and therefore, the total C emissions for 1990. For Brazil, C emissions increased 31% over the estimated 73 Tg C; India, 9%; Indonesia, 18%; and the Ivory Coast, 25%.

Discussion

Although we did not account for regrowth of forests in either of the two methods, we would expect for the forest sector as a whole that regrowth would offset a large proportion of the emissions from harvested wood and thus reduce overall emissions from this sector, making many, especially developed, countries a net C sink. As mentioned above, a reliable global database for estimating C uptake by regrowth is not readily available. However, for the four developed countries used in this paper, we estimated the C uptake from the data on net annual increment ($\text{m}^3 \text{yr}^{-1}$) reported in UN ECE/FAO (1992). No similar data are available for developing countries clearly indicating that efforts to fill such a critical void are needed. Even the UN ECE/FAO database is not consistent across the four countries. For example, three of the four countries reported net annual increment whereas one reported gross annual increment; volume is reported as both under bark and overbark; and standards for volume estimation differ [from all volume to a minimum top diameter of 0 cm (Finland), to a top diameter of 10 cm (United States),

Table 7. Summary of C fluxes estimated by the stock-change method, by categories and countries (in Tg C for 1990).

Category/ country	Roundwood production*	Slash [†]	Commodity stored $\geq 5 \text{ yr}^{\ddagger}$	Inherited emissions [§]	Total
	(1)	(2)	(3)	(4)	(5)
Developing					
Brazil	73	3	7	4	-73
India	82	1	6	3	-80
Indonesia	55	2	3	1	-56
Ivory Coast	4	0.2	0.3	0.2	-4.3
Developed					
Canada	40	15	7	1	-50
Finland	10	4	1.2	0.3	-13
New Zealand	2.7	1	0.6	0.3	-3.4
U.S.A.	123	55	57	17	-138
Worldwide					
Developing	583	18	68	42	-575
Developed	367	152	184	71	-406
Total	950	170	252	113	-981

* Column 1, Table 3

† Column 5, Table 4

‡ Column 9, Table 5

§ Column 2, Table 6

|| $-(\text{Column (1)} + \text{column (2)}) + \{\text{column (3)} - \text{column (4)}\}$, subject to rounding.

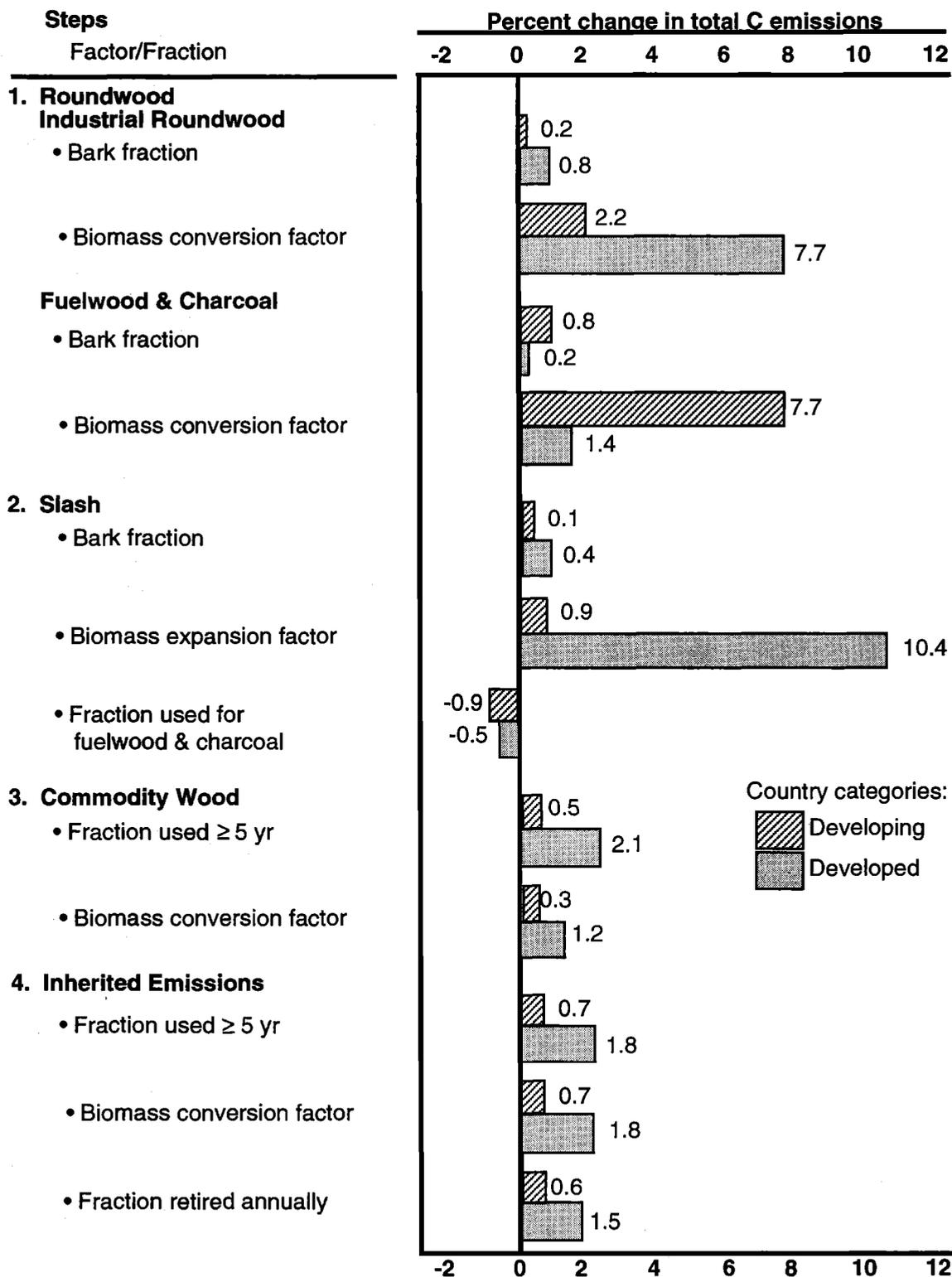


Figure 2. Percent change in total C emissions for developing and developed countries based on a 10% increase in various fractions used in a given step of the analysis.

to unknown value for the other two countries]. Despite these differences in the data, we used them to make a first-order approximation of the C uptake in net annual increment in aboveground commercial-size trees using the biomass conversion factors and biomass expansion factor (to account for bark, branches, twigs, leaves, etc.) described above in Methods.

First-order approximations of the C uptake by the annual forest increment are: 121, 24, 7.7, and 274 Tg C yr⁻¹, for Canada, Finland, New Zealand, and United States, respectively, for the mid to late 1980s. These first-order estimates of net uptake are more than enough to offset emissions from harvest and wood products, ranging from 2 to 3.4-fold larger for the atmospheric-flow method and 2 to 2.4-fold for the

stock-change method. Similar results have been reported for the same or other countries [e.g., Burschel et al. (1993) for Germany; Kurz et al. (1992) for Canada; and Karjalainen (1996) for Finland].

It was natural to look for trends in use of wood and wood commodities for the eight countries analyzed as presented in Tables 3–7. It is clear that very little roundwood is imported or exported globally, and that more exchange among countries occurs as commodities (almost three times more than roundwood). However, upon more careful study, first perceived trends usually did not always hold up. This was largely because each country, not surprisingly, had some unique forest and wood-use characteristic that makes it the exception. For example among the developing countries analyzed, India, Indonesia, and Ivory Coast used over three-quarters of their roundwood consumption for fuelwood and charcoal (Table 3). Further, the four developing countries analyzed put more commodity wood into long-term uses as sawnwood than as woodbase panels, other industrial roundwood, and paper and paperboard combined. The four developed countries stored almost an equal amount of C in paper and paperboard as in sawnwood (Table 5).

On a larger geographic scale, trends in C emissions were seen in the results for the developing- and developed-country categories. For example, forest harvesting and wood products produced C emissions in a ratio of about 60:40% between developing and developed countries regardless of method used. This was partly driven by the higher quantities of wood burned for energy as fuelwood and charcoal in the developing countries, an eight-fold larger percentage of the world total compared to the developed countries. Developing countries that use substantial quantities of wood from their forests for energy are likely to produce small net C emissions to the atmosphere from their energy sector because C emissions from biomass fuels are part of the closed C cycle. On the other hand, the proportion of total roundwood consumption used for fuelwood in developed countries is small (Table 3); instead, they use fossil fuels. Because of these differences in fuel use (wood versus fossil), a developing country using the same energy as a developed country could have smaller net C emissions to the atmosphere.

Worldwide, we estimated that the total C emissions in 1990 as a result of forest harvesting and wood use was about 1 Pg C (980 Tg C), a number that was derived by using both the atmospheric-flow and stock-change methods. This represents about 16% of the 6.1 ± 0.5 Pg C yr⁻¹ from fossil fuel burning and cement manufacturing in the early 1990s (Marland et al. 1994). The net flux to the atmosphere from changes in tropical land use (including forest clearing, forest harvesting, and regrowth) is 1.6 ± 1.2 Pg C yr⁻¹ (Schimel et al. 1995), which includes much of our flux estimates for forest harvesting in developing countries. And, as discussed before, the net C flux from the forest sector, including regrowth but *excluding* biomass burning due to deforestation, is likely to be negative, i.e., there is a net C sink.

Our estimates at the country level compare favorably with others reported in the literature. For example, Powell et al. (1993) report that removals from USA forests in 1991 totaled

approximately 166 Tg C. Our U.S. estimate for 1990 was a close 123 Tg C (Table 3). In addition, Heath et al. (1996) estimated that for 1990, the net flux into forest products in the USA was 21 Tg C. Taking equivalent components from Table 5, i.e., sawnwood at 23 Tg C and woodbase panels at 8 Tg C and adjusting them for the net C flux into these commodities in 1990 (i.e., U.S. production minus exports) the comparable total by our method was slightly higher at 30 Tg C. Of this amount, our estimate is that 25 Tg C went into uses for periods ≥ 5 years.

In Finland, Karjalainen et al. (1994) states that the current roundwood harvests contain 9.9 Tg C yr⁻¹ with a “felling residue” (i.e., slash) of 7.9 to 9.9 Tg C yr⁻¹. Our comparable estimates for Finland in 1990 were 10 Tg C (Table 3) and 4 Tg C (Table 4), respectively. Even though our slash estimate was based on a biomass expansion factor for softwoods that is likely conservative for Finland’s forests (where volume is based on the total height of the tree), our relatively low slash estimate as compared to Karjalainen et al. suggests that other factors are contributing to the high felling residues in Finnish forests. Karjalainen’s (1996) model estimate for the late 1980s is that the net C sequestration in wood products in Finland is 0.5 Tg C yr⁻¹ after accounting for exports; our comparable estimate is somewhat higher at 0.9 Tg C yr⁻¹.

The IPCC 1995 methodology assumes that all harvested wood is oxidized in the year of harvest, an assumption based on the premise that there is no net change in the store of wood products, and no accounting is made for imports or exports of roundwood and commodities. By the IPCC methodology, we estimated that the total C emissions for each country were higher than the results that we obtained from both our methods. By categories, developing countries would be overestimated, on average, by 5%, and developed countries by 28%. The overestimate for the world would be 14%. The difference between the 1995 IPCC method and our two proposed methods corresponds to the increase of wood product C stocks (139 Tg C yr⁻¹).

Results from the sensitivity analyses demonstrated the influence of the conversion factors adopted for the methods. They especially illustrated the need to be as accurate as possible in the use of biomass conversion factors. When a 10% change in the factor can make over a 7% change in the total emission estimate for a country, then this deserves careful attention and additional research focus. This was particularly evident where the amount of a particular wood component in the C emission estimate was high, e.g., industrial roundwood, commodities, and slash in the developed countries and fuelwood and charcoal for developing countries. Further, where the factors have a multiplicative function (e.g., biomass conversion and expansion factors), their influence is much greater than where they are additive (e.g., bark fractions). For example, the additional sensitivity analysis for developing countries where the biomass expansion factor was raised from 2.0 to 5.0 to account for damage to residual stand from poor logging practice, increased the estimated C emissions from 9 to 31%. This is clearly an area where a reduced impact of logging could have a significant effect

on a country's inventory of C emissions (Pinard and Putz 1996).

Implications for Policy

It has been shown in this paper that there is no difference between the two methods (1) on a global scale, (2) for countries without any exports or imports, and (3) for those wood flows that do not cross national borders. The atmospheric-flow method focused primarily on estimating net annual CO₂-C emissions for harvests and wood product uses in a country. In the stock-change method, we were not so much interested to know in which country the C emissions to the atmosphere occurred, but how forest and wood product C stocks change in various countries. Any increase of the wood product C stock decreased the total result of that country and vice versa.

We are aware that the choice of method (atmospheric-flow or stock-change method) has potential policy implications or impacts on the incentives/disincentives to use wood. For example, in an atmospheric-flow method a country burning imported fuelwood in a power station will experience no reduction in C emissions (compared to the base case where it burned coal), even if the wood was produced on a sustainable basis. Countries exporting large quantities of wood might show a great reduction of C emissions when comparing the results for the atmospheric-flow method with their emission balances prepared according to the 1995 IPCC method or the stock-change method.

It is often argued that wood should be accounted for in the IPCC Guidelines in the same way as fossil fuels. With respect to CO₂ emissions from fossil fuel burning there is consensus that these emissions should appear in the inventory of the country where combustion occurs and that the C is not accounted for until it is converted to CO₂ and becomes part of the biogeochemical cycling of C at the Earth's surface. This philosophy is embodied in the emissions methodology now in use for fossil fuels internationally (IPCC 1995) and is similar to the atmospheric-flow method for wood products described here. The choice of accounting method (atmospheric-flow or stock-change) is less clear when recyclable C is considered. Whereas for fossil C there is practically no flux back into geologic deposits, the biological cycling of C is different—consisting of C uptake via photosynthesis and C release from respiration, decomposition, or burning.

It can, therefore, be argued that cycling of renewable or biotic C should be tracked differently in the IPCC Guidelines than fossil fuel C. It also seems reasonable that all renewable C be treated in the same way. Wood fuel and agricultural products are similar in that the C is oxidized in the year of harvest. Long-lasting wood products require an accounting for the delayed release of C to the atmosphere but in the longer term they are also part of a closed cycle and thus renewable. Currently the IPCC Guidelines implicitly use a stock-change method for nonwoody C, such as agricultural products—although in most cases there is no stock change involved. Thus, no emissions show up in the national inventory of the importer, and the exporting country does not report a C sink—both balance zero. Assume that a power plant uses a mix of imported agricultural residues (straw, bagasse, etc.)

and imported wood as a fuel. The atmospheric-flow method for wood products would necessitate emissions from wood fuel to be counted in the country operating the power plant. However, this country would report no emissions from the agricultural residue. In a stock change method the country burning the biomass fuels (both wood and agricultural residue) would not report any emissions at all.

In summary, choosing the atmospheric-flow method would mean that wood is treated in the same way as fossil C but different from "agricultural" C. On the other hand, a stock-change method would treat all renewable C in the same way, but this would differ from the way fossil fuels are accounted for.

The amount of wood or agricultural products traded between countries—causing the difference between atmospheric-flow and stock-change method—may seem small compared to flows of these goods within countries. However, as soon as countries are further split up into smaller entities [e.g., states or communities and corporations (U.S. Department of Energy 1994)] and inventories are carried out for them, exports and imports will become increasingly important and can make up a considerable share of C flows. Any inventories eventually done on a small scale have to be compatible with the inventory on the national scale. When designing the methodology for national GHG balances this has to be taken into account.

Technically both the atmospheric-flow method and stock-change method are sound, but both come at the issues from a different perspective. Large exporters could favor the flow method, whereas smaller importers the stock-change method. The atmospheric-flow method favors the export of domestic wood over its use in the country of origin, whereas the stock-change method does not distinguish between export or domestic use. The atmospheric-flow method follows the philosophy now used for fossil fuels, whereas the stock-change method is similar to the accounting scheme used in the 1995 IPCC Guidelines and follows the philosophy used for agricultural products. Here we pointed out some of the policy implications embedded in the two methods but believe that these implications need further investigation and discussion.

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