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Estimates of carbon storage in wood products following land clearing

Authors: Stephanie Searle, Chris Malins

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Introduction

Production of biofuels may lead to indirect land use change (iLUC) by displacing food production onto new cropland (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Searchinger et al., 2008). The clearing of such land for expanding agriculture would result in large amounts of carbon emissions as plant biomass and soil carbon are removed or burned. It is likely that not all biomass carbon in forests would be emitted, as some wood would presumably be harvested and used in housing, furniture, etc. The fraction of cleared forest biomass that is assumed to remained stored as harvested wood products (HWP) may have a significant impact on global modelled iLUC emissions. Using GTAP, Tyner, Taheripour, Zhuang, Birur, & Baldos (2010) assume that 25% of cleared forest vegetation is stored as HWP, while Hertel et al. (2010) assume this fraction to be 10%. Many other studies modelling iLUC greenhouse gas emissions do not account for HWP or assume it to be zero (Bouet, Dimaranan, & Valin, 2010; Dumortier & Hayes, 2009; Searchinger, et al., 2008). Typically, little rationale is provided for these assumptions. In one of the few attempts to characterize the HWP factor, Mueller (2010) calculated carbon storage in HWP as a fraction of forest biomass in the United States using data from the US Forest Service; he concluded this fraction to be similar to the 25% assumption used in Tyner et al. (2010). In this report, we review the analysis presented in Mueller (2010) and conclude that the fraction of biomass carbon retained as HWP in the US is much lower, at 10%. We use two separate approaches to estimate the HWP fraction in developing nations; while uncertain, this fraction is likely even lower than in the US. As the HWP factor is an important input to models predicting iLUC emissions, we recommend that modellers either adopt the 10% assumption or perform their own in-depth analysis.

Part 1: Reviewing the analysis in Mueller (2010) of harvested wood products in the United States

Determining the fraction of total biomass in forests that is removed

The US Forest Service provides data on harvested wood that is removed from US forests, logging residues, and wood products (US Forest Service, 2007b). In Mueller (2010), the fraction of forest biomass that is removed during logging is determined by dividing the amount of wood removals by the total amount of wood felled (wood removals and logging residues) provided in the US Forest Service RPA Table 40. Using this metric, 71% of total felled wood is removed (24% of total felled wood is removed softwood and 47% is removed hardwood).

However, logging residues are only a fraction of forest total biomass that is not removed for wood products. In order to estimate the total loss of carbon that would be incurred were land cleared for agriculture (e.g. biofuels production), it is necessary to include all total biomass in this analysis. According to the definition of "logging residues" provided in RPA Table 40, as well as personal communication with Brad Smith, the Forest Inventory Associate Program Leader, components included in forest removals and logging residues are not consistent; branches may sometimes be harvested and sometimes not, and may or may not be counted in logging residues. Dead wood is included in logging residues when standing dead trees are accidentally knocked down during logging operations. However, the majority of dead wood is apparently not included in logging residues, nor are the forest floor, live understory, roots, or tree foliage. A conservative estimate of total biomass carbon unaccounted for by the Forest Service is 52% (forest floor, live understory and tree foliage, roots, and 90% of dead wood; Table 1). This estimate assumes that the Forest Service accounts for all branches and standing dead trees (snags are 10% of dead wood in managed forests; Guby and Dobbertin, 1996).

Table 1. Forest components as percentages of total biomass in the US* (Sources: Chatterjee, Vance, & Tinker, 2009; Litton, Ryan, & Knight, 2004; Peichl & Arain, 2007; Turner, Koerper, Harmon, & Lee, 1995; Whittaker, Bormann, Likens, & Siccama, 1974).

Component	% of total biomass
Live stemwood**	35
Live branches	12
Live foliage	2
Live understory	1
Forest floor	7
Dead wood	33
Roots	9

* Estimates may not add to 100% due to rounding

** Includes bark

Thus, a conservative estimate of wood removals as a fraction of total biomass would be:

Wood removals / ((wood removals + logging residues) / (1 – 0.52))

resulting in estimates of **0.23** and **0.11** of total biomass removed as softwood and hardwood, respectively, for a total of **0.34** of total biomass removed as harvested wood

(compared to 0.47 and 0.24 for softwood and hardwood, respectively, and a total of 0.71 reported in Mueller, 2010).

Determining the end use of harvested wood

The purpose of this step is to determine how much of the harvested wood is processed into sawlogs vs. pulpwood, which have different disposition patterns over time. Mueller (2010) uses the Forest Service RPA Table 39 (US Forest Service, 2007a), classifying veneer logs and sawlogs as sawlogs; and composite products, posts, poles, pilings, and miscellaneous products as pulpwood. He reports that 0.64 and 0.31 of softwood and 0.40 and 0.41 of hardwood is processed into sawlogs and pulpwood, respectively. The missing fractions (0.05 of softwood and 0.19 of hardwood) are processed into fuelwood.

Mueller (2010) did not account for the fraction of harvested wood that is lost in the milling process. Here, this fraction is determined by dividing the total mass of wood products (sawlogs and pulpwood) by the total mass of wood removals in RPA Table 40 for each of softwoods and hardwoods; this calculation yields fractions of 0.95 and 0.82 for softwoods and hardwoods and 0.91 for all wood combined. These fractions are conservative compared to those calculated from data provided in the UK Forestry Statistics (2001; 0.58 for softwood and 0.52 for hardwood) and to Ingerson (2009; 0.64 of roundwood delivered to mill in the medium scenario).

Thus, the estimates for the fractions of harvested wood processed into sawlogs and pulpwood are as follows:

Softwood: sawlogs: 0.95 (fraction of removed wood that is processed) x 0.64 (fraction of processed softwood that is sawlogs) = 0.61

Pulpwood: 0.95 x 0.31 = 0.26

Total softwood: 0.61 + 0.26 = 0.87

Hardwood: sawlogs: 0.82 x 0.40 = 0.33

Pulpwood: 0.82 x 0.41 = 0.33

Total hardwood: 0.33 + 0.33 = 0.66

Disposition patterns of harvested wood after 30 years

Mueller (2010) uses the disposition patterns supplied in Table 6 in a 2006 USDA report (Smith, Heath, Skog, & Birdsey, 2006) to calculate the fractions of wood products (sawlogs, pulpwood) that are either in-use or intact in landfills after 30 years. The resulting estimates are that 0.45 of softwood sawlogs, 0.20 of softwood pulpwood, 0.37 of hardwood sawlogs, and 0.33 of hardwood pulpwood are intact after 30 years.

The disposition patterns in Smith et al. (2006) are fairly similar to a number of independent estimates (Chen et al., 2010; Ingerson, 2011; Marland, Stellar, & Marland, 2010; Pingoud et al., 2006; Profft, Mund, Weber, Weller, & Schulze, 2009) and so are likely robust.

Determine final fraction of total biomass that remain intact after 30 years

This calculation is simply:

[fraction of forest total biomass that is removed] x [fraction of removed wood that remains after milling] x [fraction of milled wood that is processed into sawlogs and pulpwood] x [disposition patterns of each type of wood product]

This is summarized in Table 2.

Thus, **10%** of total biomass in logged forests in the US remains intact as wood products after 30 years. Were roots and dead wood to be excluded from this analysis, the fraction of aboveground live biomass remaining intact as wood products after 30 years would be 19%.

It is not possible to quantify the uncertainty of this estimate at this stage; uncertainty estimates are not available for the Forest Service data or for the HWP disposition patterns provided by the USDA. It should be understood that the final estimate given here for the fraction of US logged total biomass remaining wood products after 30 years is not precise and should be used cautiously.

Table 2. Determining final fraction of total biomass that remain intact after 30 years

	Softwood		Hardwood		Total
	Sawlogs	Pulpwood	Sawlogs	Pulpwood	
Fraction of total biomass removed*	0.23		0.11		0.34
Fraction of removed wood that remains after milling	0.95		0.82		0.91
Fraction of milled wood for each of softwood and hardwood that is sawlogs or pulpwood	0.64	0.31	0.4	0.41	0.86
Fraction of sawlog or pulpwood products that remain in use after 30 yrs	0.45	0.2	0.37	0.33	0.37
Final fraction of total biomass that remains in-use after 30 yrs	**0.06**	**0.01**	**0.01**	**0.01**	**0.10**

*Fractions are additive across categories; e.g. 0.23 of total biomass is softwood removals and 0.11 of total biomass is hardwood removals, for a total of 0.34 of total biomass that is removed, not 0.23 of softwood total biomass is removed as softwood.

Methane from HWP in landfills

We can use the fraction of total biomass that remains in-use after 30 years (see Table 2) as an indicator of avoided CO_2 emissions following deforestation. However, these estimates do not take into account greenhouse gases generated from HWP in landfills. Decomposition in landfills is largely anaerobic, and so produces about equal amounts of methane as carbon dioxide (Ingerson, 2011; Upton, Miner, Spinney, & Heath, 2008). Methane has a much higher global-warming potential than carbon dioxide, especially over the short term (72x that of CO_2 by weight over 20 years and 25x that of CO_2 over 100 years) and thus is important to account for.

Eventual methane production depends on the amount of material that is deposited in landfills (note: the estimates for sequestered carbon in HWP in the previous section were a combination of fractions of HWP in-use and material that is in landfills but not yet degraded). Table 8 of Smith et al. (2006) provides estimates of how much of each type of HWP is discarded after 30 years; combining these numbers with the fraction of discarded material that enters landfills in Table D4 provides the total amount of HWP delivered to landfills after 30 years. Classifying softwood lumber as softwood sawlogs, hardwood lumber as hardwood sawlogs, plywood as veneer, paper as pulpwood, composite products as oriented strandboard and non-structural panels, and posts, poles, and pilings as miscellaneous materials, a total of 35% of HWP will have been delivered to landfills after 30 years.

In 2000, 43% of US landfills were equipped with methane collection equipment (collected methane is then converted to fuels; EPA, 2002) Taking this into account, once all ‘short term’ decay has taken place and further methane emission is negligible, 0.038 g CH_4 will have been emitted for every 1 g of landfilled HWP (EPA, 2002). This amount of CH_4 has the same global-warming potential as 0.94 g CO_2 per 1 g landfilled material using the 100 year horizon. Assuming equal amounts of CO_2 produced as CH_4 (as discussed above), 0.064 g CO_2 is emitted per 1 g landfilled material, leading to a total of 1.01 g CO_2e (CO_2 equivalent) per 1 g landfilled material. Were discarded HWP immediately combusted to pure CO_2, 1.47 g CO_2 would be produced per 1 g material. Thus, allowing material to decay in landfills produces 69% of CO_2e as would be produced were the HWP to be immediately combusted to pure CO_2 upon discarding. This estimate is similar to that provided in Skog, (2008; 43-63%).

The captured methane (from landfills equipped to do so) is presumably used for electricity generation, offsetting CO_2 emissions that would otherwise have been incurred through burning coal, etc. EPA (2002) assumes 0.18 MTCE (metric ton carbon equivalent) per MTCE methane produced, which is equivalent to 0.495 g CO_2 per g CH_4. EPA (2002) discounted methane collection by 15% to allow for down time with collection systems. Given that 43% of US landfills captured methane in 2000 and using the 15% discount, on average 0.181 g CO_2 were offset per g CH_4, reducing the total of landfill emissions to 0.83 g CO_2e per 1 g landfilled material and 56% of of CO_2e that would be produced were the HWP to immediately combust to CO_2 upon discarding.

Thus, the 100-year global-warming potential of methane produced from HWP 30 years after land use change initially occurs would be approximately 0.56 (GWP of landfill-produced HWP methane) x 0.35 (fraction of HWP delivered to landfills) x 0.13 (fraction of total biomass converted to HWP) = 0.025; i.e. the GWP of this fraction is 2.6% of total biomass of deforested land.

This is not a dominant effect in the context of total HWP use, but is significant. While ignoring methane emission from land-filled HWP may be a reasonable first approximation, it would also be reasonable to consider modifying the HWP fraction as a modeling parameter to account for methane emissions (i.e. reducing the estimate of carbon sequestered in HWP after 30 years). However, the assessment presented here for methane emissions is methodologically different from the assessment of the HWP fraction, so while there is scope for more detailed analysis, we would not recommend directly modifying the HWP fraction using the 2.6% figure at this stage.

Part 2: Estimating the fraction of total biomass that is stored as wood products globally: Approach A

Approach

The Food and Agriculture Organization of the United Nations provides data on forestry characteristics for more than half of the world's nations (FAO, 2010). This includes: extent of forest area, estimated living biomass in forests, and production of roundwood. In order to perform a similar analysis to that presented for the US in Part 1 of this report, we require estimates of the land area or amount of biomass disturbed in land clearing and logging; however, we cannot find any previously reported estimates. Changes in the extent of forest area or in forest biomass estimated by the FAO (estimated for 1990, 2000, 2005, and 2010) are unlikely to answer this question as, globally, forests are growing in mass faster than they are being removed (R.A. Houghton, 2003).

Here, we estimate the amount of biomass cleared with the following approach. Using experimental studies tracking changes in living biomass in undisturbed plots over a number of years, we estimate the increases in biomass in various tropical regions that would have occurred without land use change. We apply these growth factors to estimates of biomass in each country in 1990 (according to the FAO data) over 10 years to predict undisturbed living biomass in 2000. We then subtract estimated actual biomass in 2000 (FAO, 2010) from these numbers to achieve estimates of living biomass lost with land use change. We estimate corresponding losses in dead wood and roots. Finally, after calculating the fraction of lost biomass that is retained in roundwood, we apply the same disposition patterns as used in Mueller (2010).

We tested this approach on the US, using an estimate of growth in regenerating Northeastern forests (Schuster et al., 2008) and obtained an estimate of lost biomass that was very similar to the estimate using the approach in Part 1 (14% difference relative to the estimate in Part 1).

We were only able to obtain sufficient experimental data on undisturbed biomass growth for tropical countries for the approximate time period of 1990-2000. Thus, we conduct this analysis for this time period.

Estimating biomass gain in tropical countries from 1990-2000

Experimental plot studies tracking changes in living forest biomass over time are available for tropical Africa, the Amazon, and Southeast Asia, with a disproportionate number of studies having been conducted in the Amazon. Table 3 summarizes these estimates in the literature. Each study was weighted in importance according to the total area covered in study plots multiplied by the number of years over which the study was conducted, and these importance values were used to weight the regional averages presented at the bottom of Table 3.

These regional growth values were applied to estimates of living forest biomass in 1990 (FAO, 2010) over 10 years to predict living biomass in 2000 had no land use change occurred. Amazon estimates were applied to South America, Central America, and the Caribbean, while tropical Africa estimates were applied to all of Africa and Southeast Asia estimates to all of south and Southeast Asia.

Estimating biomass lost to land clearing in tropical countries from 1990-2000

Estimates of actual living biomass in 2000 (FAO, 2010) were then subtracted from predicted biomass to obtain estimates of biomass lost to land use change from 1990-2000. In a few cases, these estimates were negative; it was assumed that actual growth must have been higher than the estimated regional values for these particular countries, and they were excluded from the analysis. Significant countries that were excluded for this reason include Vietnam and Malaysia.

Roundwood production as a fraction of lost total biomass

Roundwood production was then divided by the estimate of lost biomass in order to calculate harvested wood products as a fraction of total biomass. First, yearly roundwood production was averaged between 1990 and 2000. Roundwood production was reported in the FAO database as cubic meters. To convert this to mass, we utilized un-weighted averages of wood densities for all tree species reported in each region (Zanne et al., 2009) and assumed a carbon content of 50% of dry mass. In a few cases, roundwood production was greater than estimated lost biomass; it was assumed that actual growth must have been higher than the estimated regional values for these particular countries, and they were excluded from the analysis. Significant countries that were excluded for this reason include India, Kenya, South Africa, Uganda, Rwanda, Niger, and Chile.

These estimates were then averaged among countries of each major tropical region identified by the FAO; countries were weighted for importance based on extent of forests in each country.

These regional roundwood fractions were multiplied by 1.33 to account for root biomass, based on the average root:shoot ratio for trees in tropical and subtropical

Table 3. Growth rates of living biomass estimated by experimental plot studies in various tropical regions, the total size of plots, and the number of years for which the studies were conducted. Studies in Central America were combined into the Amazon category. Negative growth estimates indicate a loss of living biomass over time, rather than growth.

Region	Study	Growth rate (Mg ha^{-1} yr^{-1})	# ha	# yr
Africa	(Djomo, Knohl, & Gravenhorst, 2011)	2.21	13	N/A*
Africa	(Taylor, Hamilton, Lewis, & Nantale, 2008)	1.57	0.64	38
Africa	(Lewis et al., 2009)	0.63	163	40
Africa	(Chave et al., 2008)	0.84	40	5
Amazon	(Chave, et al., 2008)	0.29	99	10
Amazon	(Phillips, Lewis, Baker, Chao, & Higuchi, 2008)	0.62	78.9	25
Amazon	(Nascimento, Barbosa, Villela, & Proctor, 2007)	-1.42	0.75	12
Amazon	(Valencia, Condit, Muller-Landau, Hernandez, & Navarrete, 2009)	0.3	25	6.3
Amazon	(Rice et al., 2004)	1.4	9.75	2
Amazon	(de Castilho, Magnusson, de Araujo, & Luizao, 2010)	1.65	72	2
Amazon	(Rolim, Jesus, Nascimento, do Couto, & Chambers, 2005)	-1.2	2.5	22
Amazon (Costa Rica)	(Clark, 2004)	-0.7	9	4
Amazon	(Chave, Riera, & Dubois, 2001)	0.7	1	10
Amazon (Panama)	(Chave et al., 2003)	0.2	50	15
SE Asia	(Chave, et al., 2008)	0.72	243	10.17
SE Asia	(Hoshizaki et al., 2004)	-1.18	6	4
Africa		**0.64**		
Amazon		**0.45**		
SE Asia		**0.70**		

* Estimates of growth over time in Djomo et al. (2011) were made historically, using tree rings. For calculation of importance, we assigned a value of 1 year to this study.

systems in the IPCC 2006 Greenhouse Gas Inventory Guidelines. These fractions were then multiplied by 1.09 to account for dead wood (Delaney, Brown, Lugo, Torres-Lezama, & Quintero, 1998; R. A. Houghton, 2001). The resulting values represent roundwood as a fraction of total forest biomass.

Final fraction of total biomass of cleared land that is intact after 30 years

Lastly, we assumed that 42.4% of roundwood products would be in use or intact in landfills after 30 years based on the disposition patterns in Smith et al. (2006), assuming that two-thirds of roundwood was softwood and one-third was hardwood (based on US fractions). The final estimates of the percentage of total biomass lost to land clearing that is still intact after 30 years are given in Table 4.

Table 4. Final estimates of the percentage of total biomass lost to land clearing that is still intact after 30 years for tropical regions.

South America	1.4
South & Southeast Asia	0.8
Central America	0.8
Eastern and Southern Africa	1.1
Northern Africa	0.6
Western and Central Africa	0.4

This analysis covers only the developing world. A major contributor to the difference in HWP carbon storage among regions is the fraction of wood that is used for fuelwood (see Part 3; Fig. 1); as most of the developed world utilizes relatively little fuelwood, we suggest that the estimate for HWP carbon storage derived for the U.S. in Part 1 could be applied to all developed countries in North America, Europe, and Oceania.

As in Part 1, it is not possible to quantify the uncertainty of these estimates in this report. The IPCC gives a default uncertainty value of 50% for biomass estimates and roundwood production in developing nations (Pingoud, et al., 2006), so overall uncertainty in the estimates in Table 4 is likely high. Caution should be used in adopting these estimates.

Part 3: Estimating the fraction of total biomass that is stored as wood products globally: Approach B

This is a much simpler approach than that used in Part 2. Here, we assumed that logging practices everywhere are similar to those in the U.S., and again that HWP disposition patterns are similar. The only metric we used to compare wood production among different regions is the ratio of roundwood to total wood removals (roundwood vs. fuelwood). In much of the developing world, the majority of wood removals are used as fuelwood, which is assumed to be immediately combusted (Fig. 1). Thus, harvested wood production must necessarily be lower for any given amount of deforestation that occurs.

We used roundwood and fuelwood production data (averaged over the period from 1990 to 2000) from the FAO Global Forest Resources Assessment. The roundwood fraction was calculated by dividing roundwood production

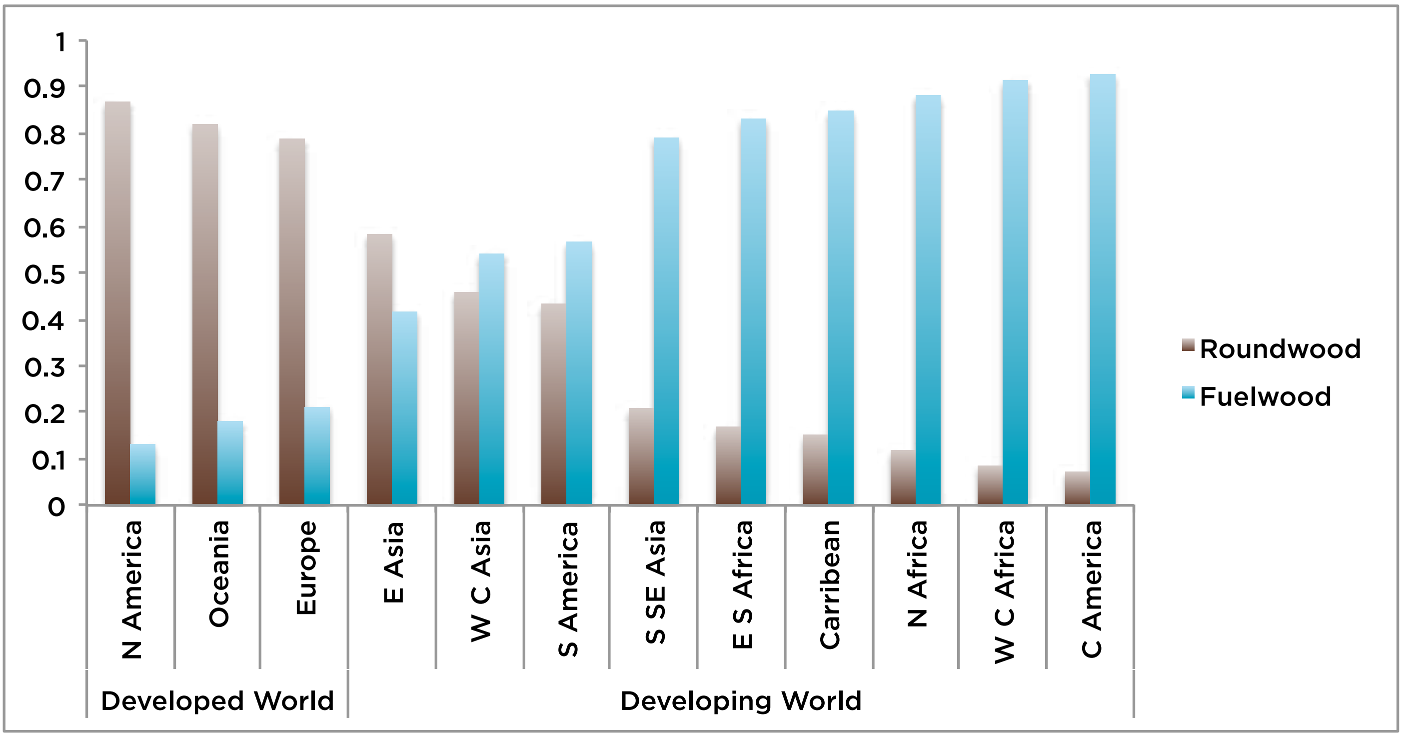

Figure 1. Fractions of total harvested wood that are used as roundwood vs. fuelwood in global regions (FAO 2010). N = North, S = South, E = East, W = West, C = Central.

by total wood production (roundwood + fuelwood). Countries were aggregated by region (shown in Figure 1); a weighted average of the roundwood fraction by total wood production was calculated. Regional roundwood fractions were relativized to the U.S. (i.e. divided by the U.S. roundwood fraction), and these relative fractions were then multiplied by the HWP fraction calculated in Part 1 (10%). Regions were then aggregated into either the developed world (Europe, North America, and Oceania, which was considered a developed region as its production is dominated by Australia) or the developing world (all remaining regions), and a weighted average of HWP fractions by total regional wood production was calculated. **The resulting HWP fractions (of total biomass) were 10% for the developed world and 3% for the developing world**. Were roots and dead wood to be excluded from this analysis, the fraction of aboveground live biomass remaining intact as wood products after 30 years would be 19% for the developed world and 6% for the developing world.

These fractions are larger than those calculated in Part 2, but in the same general range. The figures presented in this section may be considered upper limits to the HWP fraction for the developing world, as it is unlikely that logging operations are more efficient in the developing world than in the U.S. As in Parts 1 and 2, it is not yet possible to calculate uncertainty for these estimates.

Literature Cited

Bouët, A., Dimaranan, B. V., & Valin, H. (2010). Modeling the Global Trade and Environmental Impacts of Biofuel Policies: Markets, Trade and Institutions Division; International Food Policy Research Institute.

Chatterjee, A., Vance, G. F., & Tinker, D. B. (2009). Carbon pools of managed and unmanaged stands of ponderosa and lodgepole pine forests in Wyoming. *Canadian Journal of Forest Research, 39*, 1893-1900.

Chave, J., Condit, R., Lao, S., Caspersen, J. P., Foster, R. B., & Hubbell, S. P. (2003). Spatial and temporal variation of biomass in a tropical forest: results from a large census plot in Panama. *Journal of Ecology, 91*(2), 240-252.

Chave, J., Condit, R., Muller-Landau, H. C., Thomas, S. C., Ashton, P. S., Bunyavejchewin, S., . . . Losos, E. C. (2008). Assessing evidence for a pervasive alteration in tropical tree communities. *Plos Biology, 6*(3), 455-462.

Chave, J., Riera, B., & Dubois, M. A. (2001). Estimation of biomass in a neotropical forest of French Guiana: spatial and temporal variability. *Journal of Tropical Ecology, 17*, 79-96.

Chen, D. X., Li, Y. D., Liu, H. P., Xu, H., Xiao, W. F., Luo, T. S., . . . Lin, M. X. (2010). Biomass and carbon dynamics of a tropical mountain rain forest in China. *Science China-Life Sciences, 53*(7), 798-810.

Clark, D. A. (2004). Sources or sinks? The responses of tropical forests to current and future climate and atmospheric composition. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences, 359*(1443), 477-491.

de Castilho, C. V., Magnusson, W. E., de Araujo, R. N. O., & Luizao, F. J. (2010). Short-Term Temporal Changes in Tree Live Biomass in a Central Amazonian Forest, Brazil. *Biotropica, 42*(1), 95-103.

Delaney, M., Brown, S., Lugo, A. E., Torres-Lezama, A., & Quintero, N. B. (1998). The quantity and turnover of dead wood in permanent forest plots in six life zones of Venezuela. *Biotropica, 30*(1), 2-11.

Djomo, A. N., Knohl, A., & Gravenhorst, G. (2011). Estimations of total ecosystem carbon pools distribution and carbon biomass current annual increment of a moist tropical forest. *Forest Ecology and Management, 261*(8), 1448-1459.

Dumortier, J., & Hayes, D. J. (2009). Towards an Integrated Global Agricultural Greenhouse Gas Model: Greenhouse Gases from Agriculture Simulation Model (GreenAgSiM). Ames, Iowa: Center for Agricultural and Rural Development; Iowa State University.

EPA. (2002). *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks: 2nd Edition*.

FAO. (2010). Global Forest Resources Assessment (Food and Agriculture Organization of the United Nations, Trans.).

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science, 319,* 1235.

Guby, N. A. B., & Dobbertin, M. (1996). Quantitative estimates of coarse woody debris and standing dead trees in selected Swiss forests. *Global Ecology and Biogeography Letters, 5*(6), 327-341.

Hertel, T. W., Golub, A. A., Jones, A. D., O'Hare, M., Plevin, R. J., & Kammen, D. M. (2010). Effects of US maize ethanol on global land use and greenhouse gas emissions: estimating market-mediated responses. *BioScience, 60*(3), 223.

Hoshizaki, K., Niiyama, K., Kimura, K., Yamashita, T., Bekku, Y., Okuda, T., . . . Noor, N. S. M. (2004). Temporal and spatial variation of forest biomass in relation to stand dynamics in a mature, lowland tropical rainforest, Malaysia. *Ecological Research, 19*(3), 357-363.

Houghton, R. A. (2001). Counting terrestrial sources and sinks of carbon. *Climatic Change, 48*(4), 525-534.

Houghton, R. A. (2003). Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. *Tellus, 55B*, 378-390.

Ingerson, A. (2011). Carbon storage potential of harvested wood: summary and policy implications. *Mitigation and Adaptation Strategies for Global Change, 16*(3), 307-323.

Lewis, S. L., Lopez-Gonzalez, G., Sonke, B., Affum-Baffoe, K., Baker, T. R., Ojo, L. O., . . . Woll, H. (2009). Increasing carbon storage in intact African tropical forests. *Nature, 457*(7232), 1003-U1003.

Litton, C. M., Ryan, M. G., & Knight, D. H. (2004). Effects of tree density and stand age on carbon allocation patterns in postfire lodgepole pine. *Ecological Applications, 14*(2), 460-475.

Marland, E., Stellar, K., & Marland, G. (2010). A distributed approach to accounting for carbon in wood products. *Mitigation and Adaptation Strategies for Global Change, 15*(1), 71-91.

Mueller, S. (2010). Analysis of Carbon Release from Conversion of US Forest Ecosystems For Biofuels Production: University of Illinois at Chicago, Energy Resources

Center.

Nascimento, M. T., Barbosa, R. I., Villela, D. M., & Proctor, J. (2007). Above-ground biomass changes over an 11-year period in an Amazon monodominant forest and two other lowland forests. *Plant Ecology, 192*(2), 181-191.

Peichl, M., & Arain, M. A. (2007). Allometry and partitioning of above- and belowground tree biomass in an age-sequence of white pine forests. *Forest Ecology and Management, 253*(1-3), 68-80.

Phillips, O. L., Lewis, S. L., Baker, T. R., Chao, K. J., & Higuchi, N. (2008). The changing Amazon forest. *Philosophical Transactions of the Royal Society B-Biological Sciences, 363*(1498), 1819-1827.

Pingoud, K., Skog, K. E., Martino, D. L., Tonosaki, M., Zhang, X., & Ford-Robertson, J. (2006). IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 12: Harvested Wood Products (Vol. 4: Agriculture, Forestry and Other Land Use).

Profft, I., Mund, M., Weber, G. E., Weller, E., & Schulze, E. D. (2009). Forest management and carbon sequestration in wood products. *European Journal of Forest Research, 128*(4), 399-413.

Rice, A. H., Pyle, E. H., Saleska, S. R., Hutyra, L., Palace, M., Keller, M., . . . Wofsy, S. C. (2004). Carbon balance and vegetation dynamics in an old-growth Amazonian forest. *Ecological Applications, 14*(4), S55-S71.

Rolim, S. G., Jesus, R. M., Nascimento, H. E. M., do Couto, H. T. Z., & Chambers, J. Q. (2005). Biomass change in an Atlantic tropical moist forest: the ENSO effect in permanent sample plots over a 22-year period. *Oecologia, 142*(2), 238-246.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F. X., Elobeid, A., Fabiosa, J., . . . Yu, T. H. (2008). Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science, 319*(5867), 1238-1240.

Skog, K. E. (2008). Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal, 58*(6), 56.

Smith, J. E., Heath, L. S., Skog, K. E., & Birdsey, R. A. (2006). Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States *General Technical Report NE-343:* United States Department of Agriculture: Forest Service.

Taylor, D., Hamilton, A. C., Lewis, S. L., & Nantale, G. (2008). Thirty-eight years of change in a tropical forest: plot data from Mpanga Forest Reserve, Uganda. *African Journal of Ecology, 46*(4), 655-667.

Turner, D. P., Koerper, G. J., Harmon, M. E., & Lee, J. J. (1995). A carbon budget for forests of the conterminous United States. *Ecological Applications, 5*(2), 421-436.

Tyner, W. E., Taheripour, F., Zhuang, Q., Birur, D., & Baldos, U. (2010). Land Use Changes and Consequent CO_2 Emissions due to US Corn Ethanol Production: A Comprehensive Analysis: Department of Agricultural Economics, Purdue University.

Upton, B., Miner, R., Spinney, M., & Heath, L. S. (2008). The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. *Biomass and Bioenergy, 32*, 1-10.

US Forest Service. (2007a). RPA Table 39: "Volume of roundwood products harvested in the United States by source of material, species group, region, subregion, and product, 2006.".

US Forest Service. (2007b). RPA Table 40: "Roundwood products, logging residues, and other removals from growing stock and other sources by species group, region, and subregion, 2006.". http://www.fia.fs.fed.us/program-features/rpa

Valencia, R., Condit, R., Muller-Landau, H. C., Hernandez, C., & Navarrete, H. (2009). Dissecting biomass dynamics in a large Amazonian forest plot. *Journal of Tropical Ecology, 25*, 473-482.

Whittaker, H., Bormann, F. H., Likens, G. E., & Siccama, T. G. (1974). Hubbard Brook ecosystem study - forest biomass and production. *Ecological Monographs, 44*(2), 233-252.

Zanne, A. e., Lopez-Gonzalez, G., Coomes, D. A., Ilic, J., Jansen, S., Lewis, S. L., . . . Chave, J. (2009). Global wood density database (http://dhl.handle.net/10255/dryad.234).