Forest Carbon Sequestration under the U.S. Biofuel Energy Policies

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Abstract

This paper analyzes impacts of the U.S. biofuel energy policies on the carbon sequestration by forest products, which is expressed as Harvested Wood Products (HWP) Contribution under the United Nations Framework Convention on Climate Change. Estimation for HWP Contribution is based on tracking carbon stock stored in wood and paper products in use and in solid-waste disposal sites (SWDS) from domestic consumption, harvests, imports, and exports. For this analysis, we hypothesize four alternative scenarios using the existing and pending U.S. energy policies by requirements for the share of biofuel to total energy consumption, and solve partial equilibrium for the U.S. timber market by 2030 for each scenario. The U.S. Forest Products Module (USFPM), created by USDA Forest Service Lab, operating within the Global Forest Products Model (GFPM) is utilized for projecting productions, supplies, and trade quantities for the U.S. timber market equilibrium. Based on those timber market components, we estimate scenario-specific HWP Contributions under the Production, the Stock Change, and the Atmospheric Approach suggested by Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories using WOODCARB II created by VTT Technical Research Centre of Finland and modified by USDA Forest Service Lab. Lastly, we compare estimated results across alternative scenarios. Results show that HWP Contributions for the baseline scenario in 2009 for all approaches are estimated higher than estimates reported by U.S. Environmental Protection Agency in 2011, (e.g., 22.64 Tg C/ year vs 14.80 Tg C/ year under the Production Approach), which is due to the economic recovery, especially in housing construction, assumed in USFPM/GFPM. Projected HWP Contribution estimates show that the Stock Change Approach, which used to provide the highest estimates before 2009, estimate HWP Contribution lowest after 2009 due to the declining annual net imports. Though fuel wood consumption is projected to be expanded as an alternative scenario requires higher wood fuel share to total energy consumption, the overall impacts on the expansion in other timber products are very modest across scenarios in USFPM/GFPM. Those negligible impacts lead to small differences of HWP Contribution estimates under all approaches across alternative scenarios. This is explained by the points that increasing logging residues are more crucial for expansion in fuel wood projections rather than the expansion of forest sector itself, and that the current HWP Contribution does not include carbon held in fuel wood products by its definition.

Keywords: Forest Products, Carbon Sequestration, Biofuel Policies, HWP Contribution

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Introduction

The emission of carbon dioxide (CO_2) to the atmosphere has been recognized as the major factor of climate change – global warming. Efforts to reduce atmospheric emission level of CO_2 have derived various activities such as enhancing renewable energy sources, involving cap and trade programs, and sequestering carbon in nature. Among those efforts, this study pays attention to carbon sequestration in forests and wood and paper products, which is named as Harvested Wood Products (HWP) contribution, due to the following reasons: first, it is known that deforestation accounts for a significant percentage of annual worldwide CO_2 emission by 20% (EPA, 2006). Accordingly, forestry can play a significant role of carbon sinks in ecosystem by mitigating CO_2 emission. HWP can be in charge of the part of contribution directly. Second, recent energy policies head for enhancing renewable biomass instead of fossil fuels for reducing greenhouse gas emissions. Such policies are expected to affect timber market supplies by the expansion of wood energy consumption in the near or long- term future, so that carbon sequestration in forest products can be expanded as well.

The term, "HWP Contribution" is defined under the United Nations Framework Convention on Climate Change (2003). While forests remove carbon to sinks directly from the atmosphere, wood and paper products are said to make contributions in sequestering carbon by keeping it in themselves as long as they don't decay and emit carbon in forms of CO_2 or CH_4 to the atmosphere. HWP Contribution is expressed as the annual change of carbon stock stored in HWP in use or discarded by following Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

The object of this study is to explore the impact of the U.S. biofuel energy policies on carbon sequestration in wood and paper products, which is linked to HWP Contribution. The major concern is to measure how much carbon will be stored by wood and paper products under hypothetical energy policy scenarios, and the following concern is to analyze how much each policy affects accounting of carbon in forest products.

The outline for this analysis is as follows. First, we introduce our methodology of modeling the U.S. and global forest sector and of estimating carbon stocks stored in wood products. Second, we develop a few hypothetical alternative scenarios from the existing and pending U.S. energy policies. Third, we solve a partial equilibrium model in order to project the U.S. forest market demand, supply, and trade for each scenario. Fourth, carbon sequestration, represented as HWP Contribution, is estimated from the projected productions, imports, and exports for wood and paper products with conversion factors from Skog and Nicholson (2000) and Skog (2008). Fourth, we evaluate energy policies by comparing the difference between HWP Contribution.

Methodology

For estimating HWP Contribution, this study takes two major steps counting on two unique economic models; the one is the U.S. Forest Products Module (USFPM), created by USDA Forest Products Lab (FPL), performing within the Global Forest Products Model, or GFPM (Buongiorno et al., 2003). This combined model is called as USFPM/GFPM hereafter. The other is an Excel-based model named as WOODCARB II, created by VTT Technical Research Centre of Finland and modified by USDA Forest Service Lab, estimating carbon sinks in forest products. First, we solve a partial equilibrium of a global forest products market for each year over a multi-decadal projection period by using USFPM/GFPM. Simulated dynamic changes in production, supply, and trade for timber market are provided over the same period. Second, we introduce timber market estimates from USFPM/GFPM into WOODCARB II, and estimate the U.S. HWP contribution with given conversion factors and formulas.

Modeling the U.S. and Global Forest Sector

The GFPM is developed to model global competitive markets of the forest sector for 180 individual countries. It simulates the evolution of production, consumption, and trade for 14 principal categories of forest products, and changes in forest area and stock for each country. Further details of the model are described in Buongiorno et al. (2003) and Raunikar et al. (2010). The USFPM is a more specific version of the GFPM for enhancing the U.S. forest sector by providing timber market information for the U.S. regions subdivided by North, South, and West (Ince et al., 2011).

USFPM/GFPM is static in that it calculates the world spatial market equilibrium in each year. Also, USFPM/GFPM is dynamic as it operates through a system of difference equations, where the market equilibrium in a year is a function of the equilibrium of the previous year; the model simulates changes in all market components from year to year. Derivation of market equilibrium within USFPM/GFPM relies on Samuelson's (1952) discussion that the spatial market equilibrium is obtained by maximizing social surplus (the sum of producer and consumer surplus). In USFPM/GFPM, maximization of social surplus is represented as follows:

$$\text{Max} W_t = \left[\begin{array}{l} \left\{ \sum_i^I \sum_k^K \int_0^{D_{ik}^t} P_{ik}^t \left(D_{ik}^t \right) dD_{ik}^t \right\} \\ -\left\{ \sum_i^I \sum_{k_1}^{K_1} \int_0^{Y_{ik_1}^T} MC_{ik_1}^t \left(Y_{ik_1}^t \right) dY_{ik_1}^t + \sum_i^I \sum_{k_2}^{K_2} \int_0^{Y_{ik_2}^T} MC_{ik_2}^t \left(Y_{ik_2}^t \right) dY_{ik_2}^t \right\} \\ -\left\{ \sum_i^I \sum_j^J \sum_k^K c_{ijk}^t T_{ijk}^t \right\} \end{array} \right] \quad (1)$$

, where the superscript t indicates a particular year, and the subscripts i and j stand for regions or countries importing from and exporting to. While the GFPM refers to i and j as individual countries only, USFPM/GFPM allows the U.S. subregions to be treated as an individual region which can import and export raw materials amongst themselves, and trade final products to the countries other than the U.S. In the GFPM, the subscript k stands for 14 principal categories of forest products classified as wood and non-wood fiber raw materials (industrial and other industrial roundwood, recovered paper, and non-wood pulp), intermediate products (mechanical and chemical wood pulp), and end products (sawnwood or lumber, plywood, particleboard, fiberboard, newsprint, printing and writing paper, other paper and paperboard, and fuelwood). Both k_1 and k_2 are subsets of k, where k_1 denotes all fiber raw materials, and k_2 indicates all intermediate and final products. For the more detailed analysis in the U.S. forest sector, the USFPM expands products categories suggested in the GFPM by adding agricultural short-rotation woody crop (SWRC) and wood residues (logging residues from timber harvesting, softwood and hardwood fiber residues from lumber and plywood/veneer production, and fuel residues from lumber, plywood/veneer, and pulp production).

The global social surplus in a particular year W_t is decomposed into three parts of consumer surplus, producer surplus, and transportation costs. Consumer surplus is defined as the sum of integrals of the inverse demand functions $P_{ik}^t\left(D_{ik}^t\right)$ over all K forest products consumed in all I regions at year t, where D_{ik}^t is the corresponding end-product demand. Producer surplus is separated into two parts by the type of products of whether they are raw materials (k_1), or intermediate and final products (k_2) because each marginal cost shows different property. For raw materials, $MC_{ik_1}^t$ stands for the marginal cost of producing k_1 products, and $MC_{ik_2}^t$ is the marginal cost of the exogenous inputs of labor, capital, and energy associated with manufacturing intermediate and final products (Raunikar et al., 2010). Here, $Y_{ik_1}^t$ and $Y_{ik_2}^t$ are supplied or produced quantity in region i at year t for k_1 and k_2 products, respectively. The last component indicates total transportation costs of trading all K products between region i and j in year t, where T_{ijk}^{t} is traded quantities for product k from region i to region j, and c_{ijk}^{t} represents the associated unit transportation cost. Unlike the USFPM, the GFPM does not support trade of wood residues between countries, so that residues from product k are assumed to be transported only amongst the U.S. subregions.

The object function in Equation (1) is subjected to the "material balance constraints"[2] that each product's total demand including exports should be less than or equal to the total supply with imports for each region (Raunikar et al., 2010; Ince et al., 2011), which is represented as follows:

$$D_{ik}^{t} + \sum_{n}^{N} a_{ikn}^{t} Y_{in}^{t} + \sum_{j}^{J} T_{ijk}^{t} \leq Y_{ik}^{t} + \sum_{j}^{J} T_{jik}^{t} \qquad \forall i, k = \{k_1 \cup k_2\} \qquad (2)$$

In the left hand side of Equation (2), the first factor D_{ik}^{t} implies the total demand quantities for product k in each region i at year t. The second component accounts for products transformation among raw materials, intermediate, and end products. That is, Y_{in}^{t} indicates quantities of other product n (intermediate or end products) which uses product k (raw materials or intermediate products) as an input factor. a_{ikn}^{t} is the input-output coefficient of transforming from product k into other product n. The last component is all exported quantities of product k from region i to region j at year t. The right hand side of Equation (2) is composed of supplied or produced quantities Y_{ik}^{t} and imported quantities T_{jik}^{t} from all J regions other than region i.

Solving the objective function (Eq. (1)) subjected to constraints (Eq. (2)) derives market equilibrium for all K products for all I countries at year t. This is performed by using the modeling

[2] The material balance constrains are crucial in calculating market equilibrium. In addition to those constraints, USFPM/GFPM employs "trade inertia" constraints in terms of dynamic shifts in trades. Details can be found in Raunikar et al. (2010) and Ince et al. (2011).

system called as the Price Endogenous Linear Programming System, or PELPS (Gilless and Buongiorno, 1985; Lebow et al., 2003). While PELPS is based on linear programming, the objective function in Eq. (1) is expressed as a quadratic form. Therefore, this study utilizes the latest version of PELPS, "qPELPS", which employs quadratic programming (Zhu et al., 2009).

USFPM/GFPM provides simulation of multi-decadal changes in market demands, supplies, trades, and forest stocks for all commodities for all regions by its dynamic property. The market equilibrium in a year is linked to the equilibrium in the following periods by exogenous and endogenous variables such as changes in manufacturing costs, price elasticity with respect to GDP, projected annual GDP growth rates, periodic forest stock or area growth rates, and so on (Buongiorno et al., 2003; Zhu et al., 2009; Raunikar et al., 2010).

Estimating HWP Contributions

Solving USFPM/GFPM, we obtain the multi-decadal projections of production, supply, imports and exports for all K products for the U.S. by a particular year. Using on those projections, we estimate variables to be used for calculating annual carbon changes in forest products, or HWP, with given conversion factors and formulas following the IPCC (2006) Guidelines. For estimating carbon stock, we introduce three accounting approaches suggested by IPCC (2006): the Stock Change Approach, the Production Approach, and the Atmospheric Approach. The Stock Change Approach estimates annual carbon stock changes in HWP and forests located in a region ignoring their origin, which means that imports are counted as the carbon stock, but not exports. On the contrary, the Production Approach focuses on the origin of HWP and forests wherever they are traded. As a result, exports are included in accounting, but not imports. Finally, the Atmospheric Flow Approach estimates annual carbon fluxes from HWP and forests to the atmosphere in a country; i.e., carbon emissions from HWP and removals by forests are mainly considered in this approach (Figure 1).

The annual changes of carbon stock in HWP are classified as the four annual changes in carbon stored 1) in HWP in use from domestic consumption and imports, 2) in HWP in solid-waste disposal sites (SWDS), 3) in HWP in use from domestic harvest, 4) in HWP in SWDS from domestic harvest (IPCC, 2006; Skog, 2008; EPA, 2011).

Let's denote the carbon stock stored in HWP in use from domestic consumption including imports as X, and assume that particular forest products become to be in use in any year T after 1990. T indicates the year when those forest products are initially included in "HWP in use." Also, let's denote t as the current year for which annual change in HWP carbon stock is being estimated. Then, the remaining amount of carbon stock stored in HWP in use from domestic consumption including imports at t is expressed as follows (McKeever, 2004; Skog, 2008):

$$X_{lm}^{T}(t) = e^{\left(-\alpha_m^T \cdot (t-1900)\right)} \cdot \sum_{l}^{L} \beta_l \cdot \left(Y_l^T + \sum_{j}^{J} T_{j\,i=\text{U.S.}\,l}^{T} - \sum_{j}^{J} T_{i=\text{U.S.}\,jl}^{T} \right) \cdot \gamma_{lm}^{T} \qquad \text{, for } l \subset k \qquad (3)$$

Like the previous section, the subscripts i and j represent regions or countries. As we deal with the U.S. forest sector solely in this section, we omit the subscript i; i.e., i corresponds to the United States with their subregions (North, South, and West). The subscript l, a subset of k in the previous section, covers forest end products (sawnwood or lumber, plywood, particleboard, fiberboard, newsprint, printing and writing paper, other paper and paperboard). Another subscript m implies end-use categories made by product l, such as single-family or multifamily housing, residential upkeep and improvement, and all paper and paperboard uses. The first component in the right hand side of Eq. (3) accounts for discard rates of end-use commodity m in exponential form. The coefficient α_m^T is the annual rate at which end-use category m is discarded from use at the year T. According to Skog (2008), α_m^T is given as

$$\alpha_m^T = \frac{\ln(2)}{\mathrm{HL}_m^T} \tag{4}$$

, where HL_m^T indicates the half-life in years for end-use m in year T. The second summation term represents the annual amount of carbon inflows from all L products which are be in use in year T. For each forest product l, Y_l^T is produced quantities, and both $\sum_j^J T_{ji=\text{U.S.}l}^T$ and $\sum_j^J T_{i=\text{U.S.}jl}^T$ stand for quantities imported from and exported to all J countries other than the U.S., respectively. So, the terms within the parenthesis correspond to consumption of end product l, as consumption is defined to be the sum of production and imports net exports. The coefficient β_l is the conversion factor from the unit for forest products (million cubic meter (MCM)) into the unit measuring carbon stocks (metric tons of carbon per year (Mg C/ year)) for each product l, which is described in Table 1. Then, the summation of the product of β_l and consumptions over L products is interpreted as the annual amount of carbon inflows into HWP in use from domestic consumption in year T. The last coefficient γ_{lm}^T is the fraction of primary product l to be in use for end-use m in year T (Skog, 2008, Table 3). From Equation (3), the total carbon held in HWP in use from domestic consumption is defined as:

$$X(t) = \sum_{T=1900}^{t} \sum_{l}^{L} \sum_{m}^{M} X_{lm}^T(t) \tag{5}$$

That is, we can estimate the total carbon stock held in all L products used in all M end-use categories from T =1900 to the current year t. Also, from Equation (5), the annual carbon change stored in HWP in use from domestic consumption for the current year t is written as:

$$\Delta X(t) = X(t) - X(t-1) \tag{6}$$

Estimating annual change in carbon held in HWP in use from domestic harvest in the U.S. is branched from Equation (3) and (6), but it's modified in terms of carbon inflows because carbon held in HWP in use comes from domestic harvest not from consumption. In this case, products harvested in the U.S. solely are considered; i.e., any U.S. products made by imported woods, which are harvested in foreign countries, are excluded, while exported woods, which are harvested in the U.S., are included in carbon inflows. When H is denoted as carbon stored in HWP in use from domestic harvest, Equation (3) is modified as follows:

$$H_{lm}^{T}(t) = e^{\left(-\alpha_m^T \cdot (t-1900)\right)} \cdot \sum_{v=1}^{V=2} \left\{ \begin{array}{l} \mathbf{1}\{v=1\} \cdot \sum_{l \subset \bar{l}_p}^{\bar{L}_p} \beta_l \cdot Y_l^T \cdot \left(\dfrac{Y_{v=1}^T - \sum_j^J T_{ji=\text{U.S.}v=1}^T + \sum_j^J T_{i=\text{U.S.}jv=1}^T}{Y_{v=1}^T} \right) \\ +\mathbf{1}\{v=2\} \cdot \left(\begin{array}{l} \sum_{l \subset l_P}^{L_P} \beta_l \cdot Y_l^T \cdot \left(\dfrac{Y_{v=2}^T - \sum_j^J T_{ji=\text{U.S.}v=2}^T + \sum_j^J T_{i=\text{U.S.}jv=2}^T}{Y_{v=2}^T} \right) \cdot \left(1 - f_{nf}^T\right) \cdot \left(1 - f_{wi}^T\right) \\ + \sum_{w=1}^{W=3} \sum_j^J \beta_w \cdot T_{i=\text{U.S.}jw}^T \end{array} \right) \end{array} \right\} \cdot \gamma_{lm}^T \tag{7}$$

In Equation (7), carbon inflows are divided into two parts by the subscript v, which stands for whether the input for product l is sawlogs (v=1) or pulpwood (v=2). Accordingly, L products are distinguished from all paper products denoted as l_p whose input source is pulpwood (v=2) and products other than paper products with the subscript $\overline{l}_p$, which include lumber, plywood, and miscellaneous end products made by sawlogs (v=1). In order to count the carbon stock in HWP harvested only from the U.S., we calculate the ratio of the net production (production plus export minus import) to production in the U.S. for sawlogs, and multiply the ratio and produced quantities of $\overline{L}_p$. The amount of carbon inflows is calculated through the corresponding conversion factor β_l. The part for pulpwood (v=2) is more complicated as it includes recovered paper products in the accounting. The summation term, which is calculated similarly with the previous case of sawlogs, is multiplied by two fraction factors, where f_{nf}^{T} is the fraction of total fiber used to make paper and paperboard of nonwood fiber, and f_{wi}^{T} is the fraction of woodpulp used to make paper and paperboard imported to the U.S. in year T. The last summation term accounts for the total amount of exported carbon stored in paper products from the U.S. in year T, where the subscript w is the type of paper products; w=1,2, and 3 indicate recovered fiber pup, recovered paper, and woodpulp, respectively. Like Equation (5) and (6), the total stock of carbon held in primary products included in end-use categories in year T is denoted as $H(t)$, and its annual change is denoted as $\Delta H(t)$. Then, they are expressed as:

$$H(t) = \sum_{T=1900}^{t} \sum_{l}^{L} \sum_{m}^{M} H_{lm}^{T}(t) \tag{8}$$

$$\Delta H(t) = H(t) - H(t-1) \tag{9}$$

Fractions and factors associated with Equation (7) are described in detail in Table 5 of Skog (2008).

In addition to HWP in use from domestic consumption and harvest, it will be meaningful to estimate the annual change in carbon held in solid-waste disposal sites (SWDS) from domestic products and harvest because discarded HWP also make a contribution to restraining carbon emission to the atmosphere in part. SWDS are assumed to have two types of discard place; dump, where oxygen works for decomposing discarded HWP over time, and landfills, where oxygen is isolated, so that HWP doesn't decay permanently; until oxygen is not fully shut off, HWP in landfills in part decay and emit carbon to the atmosphere temporary.

We estimate carbon in HWP in SWDS under two cases represented by the subscript $u=1$ for the permanent case, and $u=2$ for the temporary case according to the degree of decay. Also, we set up another subscript w to let the temporary case include both cases of carbon stock in dumps ($w=1$) and in landfills ($w=2$). Let's denote q as the process after HWP are discarded. q is categorized as: q = 1 to go to SWDS including dumps and landfills; q = 2 to go to SWDS and dumps rather than landfills; q = 3 to be burned without energy production; q = 4 to be recycled; q = 5 to be composted; and q = 6 to be emitted to the atmosphere. For each product l , f_{lq} indicates the fraction that product l corresponds to the process q . When products are initially discarded at year T , the carbon stock of HWP in SWDS is denoted as $\tilde{X}$ for HWP from domestic consumption and $\tilde{H}$ for HWP from domestic harvest, respectively.

$$\begin{aligned}\tilde{X}(t) = \quad & \mathbf{1}\{u=1\}\cdot\left(\sum_{T=1900}^{t}\sum_{l}^{L}\beta_l\cdot\delta_l\cdot\left(Y_l^T+\sum_{j}^{J}T_{ji=\text{U.S.}l}^{T}-\sum_{j}^{J}T_{i=\text{U.S.}jl}^{T}\right)\cdot f_{lq=1}\cdot\prod_{q=2}^{Q=5}\left(1-f_{lq}\right)\right) \\ & +\mathbf{1}\{u=2\}\cdot\left(\sum_{T=1900}^{t}\sum_{l}^{L}\sum_{w=1}^{W=2}e^{\left(-\alpha_{lw}\cdot(t-T)\right)}\cdot\beta_l\cdot\delta_l\cdot\left(Y_l^T+\sum_{j}^{J}T_{ji=\text{U.S.}l}^{T}-\sum_{j}^{J}T_{i=\text{U.S.}jl}^{T}\right)\cdot f_{lq=1}\cdot\left(\mathbf{1}\{w=2\}+(-1)^{w-1}\cdot f_{q=2}^{*}\right)\right)\end{aligned} \tag{10}$$

$$\Delta\tilde{X}(t)=\tilde{X}(t)-\tilde{X}(t-1) \tag{11}$$

$$f_{lq=1} = 1 - f_{lq=3} - f_{lq=4} - f_{lq=5}$$, for each l (12)

, where β_l, δ_l, and Y_l^T are conversion factor, discard rate, and quantity of HWP for each product l at year T, so that the multiplication of three factors is the amount of carbon discarded from product l. $f_{q=2}^*$ is the fraction of all wood and paper products that are discarded to SWDS that go to dumps rather than landfills in year T. The annual change in carbon held in HWP in SWDS from domestic consumption is described in Equation (11).

Estimating carbon held in HWP in SWDS from domestic harvest $\tilde{H}(t)$, and its annual change $\Delta H(t)$ follow the same arguments from Equation (10) ~ (12).

$$\begin{aligned}\tilde{H}(t) = \; & \mathbf{1}\{u=1\} \cdot \left(\sum_{T=1900}^{t} \sum_{l}^{L} \beta_l \cdot \delta_l \cdot \left(Y_l^T - \sum_{j}^{J} T_{ji=\text{U.S.}l}^{T} + \sum_{j}^{J} T_{i=\text{U.S.}jl}^{T} \right) \cdot f_{lq=1} \cdot \prod_{q=2}^{Q=5} \left(1 - f_{lq}\right) \right) \\ & + \mathbf{1}\{u=2\} \cdot \left(\sum_{T=1900}^{t} \sum_{l}^{L} \sum_{w=1}^{W=2} e^{(-\alpha_{lw} \cdot (t-T))} \cdot \beta_l \cdot \delta_l \cdot \left(Y_l^T - \sum_{j}^{J} T_{ji=\text{U.S.}l}^{T} + \sum_{j}^{J} T_{i=\text{U.S.}jl}^{T} \right) \cdot f_{lq=1} \cdot \left(\mathbf{1}\{w=2\} + (-1)^{w-1} \cdot f_{q=2}^{*} \right) \right)\end{aligned} \quad (13)$$

$$\Delta\tilde{H}(t) = \tilde{H}(t) - \tilde{H}(t-1) \quad (14)$$

The only difference is that the discarded amount should come from the U.S. domestic harvest, and exports also should be added in Equations. All the associated ratios such as β, δ, and f are not described here. Instead, we recommend to refer to Table 3, 6a, and 6b in Skog (2008).

Based on estimates from Equation (3) ~ (12), HWP Contributions are computed for each year using three accounting approaches documented previously.

$$\Delta H(t)+\Delta\tilde{H}(t) \tag{15}$$

$$\Delta X(t)+\Delta\tilde{X}(t) \tag{16}$$

$$\Delta X(t)+\Delta\tilde{X}(t)-\sum_{l^*}^{L^*}\sum_{j}^{J}\beta_{l^*}T_{ji=\text{U.S.}l^*}+\sum_{l^*}^{L^*}\sum_{j}^{J}\beta_{l^*}T_{i=\text{U.S.}jl^*} \tag{17}$$

Equation (15), (16), and (17) indicate HWP Contribution under the Production, the Stock Change, and the Atmospheric Flow Approach, respectively. Carbon stock in imports and exports in Equation (17) are expressed as the summation terms; the first summation term corresponds to carbon in imports, and the second carbon in exports. Those imports and exports include logs, chips, woodpulp, and recovered paper. They are separate from imports and exports used in Equation (3) ~ (16), so we denote them as the subscript l^* not l as we have denoted.

ANALYSIS

We focus on impacts of biofuel energy policies on the HWP Contribution projection. In order to investigate how HWP Contribution for carbon sequestration varies by different energy scenarios, we design a few hypothetical energy policies. This study is on the basis of the U.S. Renewable Fuels Standard policy (RFS) created under the Energy Policy Act of 2005 and revised by the Energy Independence and Security Act of 2007. In addition to RFS, we consider pending national renewable energy standards (RES) legislation. Hypothetical future scenarios are developed by combining RFS and RES which require various percentages of electric power to be generated from non-hydroelectric renewable energy sources. Those scenarios refer to the 2010 U.S. Annual Energy Outlook (AEO) (U.S.

DOE, 2010a) providing the U.S. renewable energy projections under key economic assumptions based on IPCC (2000).

Employing Ince et al. (2011), we set up four alternative scenarios in abbreviation as follows: 1) RFS+RES10, 2) RFS+RES20+EFF, 3) RFS+RES20, and 4) RFS+RES20+HP. First, the RFS+RES10 scenario assumes a continuation of the existing federal level RFS and RES, where 10% of electricity is required to be generated from non-hydro renewable energy sources by 2030. It's used as our baseline scenario as it reflects the current U.S. energy policies considerably. Second, the RFS+RES20+EFF scenario increases electricity requirement from non-hydro renewable sources up to 20% by 2030 under the RES with the same RFS. In addition, it assumes half of the biomass energy operates at the efficient combined heat & power (CHP) plants. Third, the RFS+RES20 scenario relaxes the requirement associated with CHP, so the RFS+RES20 scenario is called as the low cogeneration case while the RFS+RES20+EFF scenario is named as the high cogeneration case. Lastly, the RFS+RES20+HP scenario is a continuation of the third scenario, but it employs the AEO High Oil Price case while the others are based on the AEO Reference case.

In this study, wood is presumed to form a third of biomass requirements suggested in the RFS and RES. This assumption is based on recent related studies, which set up them as about 30% (USDOE, 2010b) or 28% (USDOE, 2007). Also, for all countries other than the U.S., the share of fuelwood to total primary energy consumption, provided by the U. S. Energy Information Administration (EIA) (2009), is assumed to be constant from 2006 through 2030 in order to focus on the impact of the U.S. energy policies only. In USFPM/GFPM, the GDP growth rate is used as a major driver for shifting demand. While the previous studies using the GFPM is based on the IPCC projection (Turner et al., 2006; Raunikar et al., 2010), we count on IMF sources between 2006 and 2014 (IMF, 2009), and use IPCC B2 message after 2015 through 2030 (IPCC, 2001). This ensures that this study reflects recent global economic recession in reality.

After solving USFPM/GFPM for each alternative scenario, we incorporate data for production, supply, and trade into WOODCARB II in order to estimate carbon stock stored in HWP components. WOODCARB II provides all information mentioned in the previous section: conversion factors, associated fractions, discard rates, the half-lives for each forest product. Estimated HWP variables and Contributions are validated by calibrating estimates with two independent sources of total carbon in housing in 2001 to census-based estimates (U.S. Census Bureau, 2003) and of wood and paper discarded to SWDS to EPA estimates for the period 1990 to 2001 (U.S. EPA, 2002; 2006) within WOODCARB II.

Results

Figure 2 illustrates the main result of the first stage, which solves USFPM/GFPM and projects future timber market. The U.S. fuel wood consumption is projected to be expanded by 2030 as the policy scenario is assumed to enhance more biomass-based energy, or to increase the share of wood to total primary energy consumption. For instance, in 2030, the total fuel feedstock consumption under the RFS+RES20+HP scenario is projected highest among four alternative scenarios. It's higher than the baseline scenario (RFS+RES10) projection by 84.17%, which is followed by the RFS+RES20 (35.42%) and the RFS+RES20+EFF (27.96%) (Table 2). However, timber products other than the fuel feedstock seem to be little affected across the alternative energy policies. For example, Table 3 indicates that projected productions for primary products (lumber, structural and nonstructural panels, wood pulp, and paper & paperboard) in a scenario are not so different from those in other scenarios as they are for fuel feedstock. Ince et al. (2011) argues that the policy-driven expansion for fuel wood results from projected increment for wood residues rather than the expansion of forest sector itself as indicated in Table 3.

As the U.S. utilizes the Production Approach in reporting HWP Contribution, this section mainly presents estimates for HWP variable under the Production Approach. Also, estimates for the Stock

Change and the Atmospheric Flow Approach are presented for supplementary explanation. As a baseline policy, we show results for the RFS+RES10 scenario, and compare them with the estimates documented in EPA (2011) for understanding how they differ from each other. Based on the produced, supplied, and traded quantities projected from USFPM/GFPM, the U.S. HWP Contribution for the RFS+RES10 scenario is estimated as 29.87 Tg C/ year (or -109.53 Tg CO_2 eq./ year) on average under the Production Approach between 1990 and 2009, which is almost equivalent to estimate of 29.48 Tg C/ year (or -108.08 CO_2 eq./ year) in EPA (2011). In addition, it's calculated as 35.33 Tg C/ year for the Stock Change Approach, and 32.40 Tg C/ year for the Atmospheric Flow Approach on average during the same period. Also, they are very close to the annual average estimates from EPA (2011); 34.53 Tg C/ year under the Stock Change Approach, and 31.60 Tg C/ year under the Atmospheric Flow Approach. This closeness of estimates between the RFS+RES10 scenario and EPA (2011) results from the same factors, such as decay rates, the half-lives, discard rates, and all associated fractions, used in WOODCARB II. However, in 2009, HWP Contributions for the RFS+RES10 scenario are estimated higher than in EPA (2011) as 22.64 vs. 14.80, 26.12 vs. 11.42, and 26.82 vs. 18.63 Tg C/ year under the Production, the Stock Change, and the Atmospheric Flow Approach, respectively (Table 4). This is due to the projected gradual recovery for the forest products in USFPM/GFPM assuming recovery from economic recession, especially recovery of housing construction.

In addition to estimates described in Table 4, Figure 3 illustrates the U.S. HWP Contributions projected by 2030 under three different approaches. Explanation for trends from 1990 through 2005 counts on Skog's (2008) arguments; the decline between 1990 and 2001 under the Production Approach results from outstanding declines in paper products in use and in SWDS. The overall increment from 1990 to 2005 under the Stock Change Approach seems to be due to increased HWP imports, whose carbon emission seems to reduce estimates under the Atmospheric Flow Approach up to 2001. Between

2006 and 2008, estimated HWP Contributions have dropped for all approaches. Those declines can be accounted for by impacts of the recent global economic recession started in 2006 on timber market.

However, after 2008 when the estimates are at the base, HWP Contributions are projected to increase through the whole projection period by 2030 under all approaches. Such upward tendencies are also associated with projected expansion of forest sector based on the recovery assumption for timber markets in USFPM/GFPM. The annual average of projected HWP Contributions between 2010 and 2030 is highest for the Atmospheric Flow Approach, 49.74 Tg C/ year (-182.4 Tg CO_2 eq./ year), followed by the Production Approach, 39.19 Tg C/ year (-143.7 Tg CO_2 eq./ year), and the Stock Change Approach, 49.74 Tg C/ year (-123.75 CO_2 eq./ year). Under the Stock Change Approach, HWP Contribution is estimated on average highest between 1990 and 2008, but on average lowest after 2008. On the contrary, the Production Approach, which estimated HWP Contribution lowest up to 2008, provides higher estimates than the Stock Change Approach did after 2008. This reverse is due primarily to the declining net imports against the constant or increasing production for solidwood products, projected by 2030 in USFPM/GFPM.

Details for estimated HWP variables through Equation (3) ~ (17) in terms of HWP Contribution are provided by approach in Table 5. Annual changes of carbon stock held in HWP in SWDS from domestic consumption and harvest are constant or slightly increasing between 1990 and 2030. But, annual changes of carbon stock for HWP in use from domestic consumption and harvest show sharp declines from 2006 through 2008, which lead to declining HWP Contributions under the Stock Change and Production Approach. As described before, this downturn results from the economic recession, especially from the shrinking of housing construction. After that period, they are projected to increase gradually by the assumption of economic recovery. Annual imports of wood and paper products (roundwood, chips, residue, pulp, and recovered paper) show a continuous decline since 2005 while their annual exports are constant or slightly increasing. Consequently, annual net imports are declining, and HWP Contribution estimated under the Atmospheric Flow Approach is projected to increase.

When estimated HWP Contributions by approach in the baseline scenario are compared with other hypothetical alternative scenarios (the RFS+RES20+EFF, the RFS+RES20, and the RFS+RES20+HP scenario), differences among scenarios appear to be very small. For instance, averages of HWP Contributions between 2010 and 2030 under the Production Approach are 36.95 Tg C/ year for the RFS+RES10, 37.33 Tg C/ year for the RFS+RES20+EFF, 37.35 Tg C/ year for the RFS+RES20, and 37.23 Tg C/ year for the RFS+RES20 + EFF. This negligible impact across scenarios is consistent with Ince et al.'s (2011) conclusion that market impacts of expansion in wood energy consumption are negligible for timber and forest products because supplies of logging residues are projected to increase for expanding fuel wood consumption instead of the expansion in timber market itself. Those differences appear to be much smaller in estimating HWP Contributions because carbon stock stored in fuel wood is not included in the carbon accounting described in Equation (3) ~ (16). Even though productions for fuel feedstock are projected to be expanded by scenarios of higher requirements for biomass in USFPM/GFPM, associated impacts don't affect the estimation for HWP Contribution under the Production and the Stock Change Approach. Table 6 presents comparison for expansions in estimated HWP Contributions across scenarios by approach. Expansions in HWP Contributions between 2006 and 2030 are largest in the highest wood energy demand scenario (the RFS+RES20+HP scenario) for all approaches, but differences are still small over scenarios. The most modest increment in 2030 is the estimation under the Stock Change Approach, which is due to declining net imports for timber products.

Conclusion

In order to analyze how much carbon can be sequestered by the U.S. wood and paper products, this study provides estimates of HWP Contributions under approaches suggested by IPCC (2006). For that, we estimate HWP Contribution and its associated variables, such as annual change of carbon held in HWP in use and in SWDS from domestic consumption, harvest, imports and exports, for the hypothetical alternative U.S. biofuel energy policy scenarios. Our analysis is performed by two steps: solving the U.S. domestic forest partial equilibrium model using USFPM/GFPM, and estimating HWP Contribution using WOODCARB II.

Between 1990 and 2009, the pathways of HWP Contribution estimates under each approach for each scenario are almost consistent with the results provided by EPA (2011) except for one in 2009, when our results are overestimated than those of EPA (2011) due to the assumption of fast economic recovery in USFPM/GFPM. Estimates reflect the recent economic recession, presenting sharp dropping in HWP contributions between 2006 and 2008, due to shrinking of housing construction. Also, results show that estimated HWP Contributions under each approach are projected to increase in the long run by 2030 set up as a target year for all alternative scenarios. For each scenario, estimated average HWP contributions are highest under the Stock Change Approach, followed by the Atmospheric Flow and the Production Approach, before 2009, but the order is changed after 2009; the Stock Change Approach provides the lowest average HWP contribution estimates due to the continuous declining in projected net imports.

Though each scenario-specific estimates for HWP Contributions provide explanation about how much carbon are sequestrated by forest products under each approach, differences across alternative scenarios are very small; that is, enhancing wood fuel energy through alternative scenarios seem to impact little on expanding the carbon stock held in forest products, HWP Contribution. This negligible impact is due to the followings: first, it is by the increment of logging residues that fuel wood consumptions are projected to be expanded across scenarios, not by the expansion of forest sector itself. Second, HWP Contributions under the Production and Stock Change Approach don't include fuel wood in calculating carbon stock held in forest products by definition because fuel wood is expected to be combusted as energy sources and emit a portion of carbon to the atmosphere. Fuel wood is included only when imports and exports under the Atmospheric Flow Approach are estimated. As a result, HWP Contribution estimates don't reflect policy-driven expansion in fuel wood market across alternative scenarios. However, combustion of fuel wood is expected to emit lower carbon than that of fossil fuels. From the views of such relative advantages of fuel wood, if alternative methods to include fuel feedstock are considered in calculating HWP Contribution, differences between scenarios can be partially bigger.

This study is limited in that it is based on the static partial equilibrium model, where dynamic property of USFPM/GFPM indicates just a series of market equilibrium over projection period. That is, we didn't consider the potential of dynamics in terms of inter temporal surplus of timber market. This study is also limited in addressing land use change between agricultural and forest sector by ignoring the expected interaction based on general equilibrium. Consideration for dynamics and general equilibrium to the model is remained as a future work.

This study makes the following contributions in the field of carbon sequestration: first, we suggest empirical calculation of carbon sequestration expressed as HWP Contribution by applying approaches following IPCC (2006) guideline under hypothetical policy scenarios. If other U.S. policies in terms of biofuel are hypothesized, this study can provide estimates of carbon sequestration in timber products projected under those policies. Second, our analysis is based on more detailed specification for wood and paper products and for the U.S. subregions. This specified analysis will provide policy makers with needs to legislate species- and state- specific biofuel energy policies by suggesting how carbon sequestration differs by products or regions. Specified regulations by species and region will diversify forest land owners' decision making, such as forest species selection, forest management practices, and disposition of the forest products.

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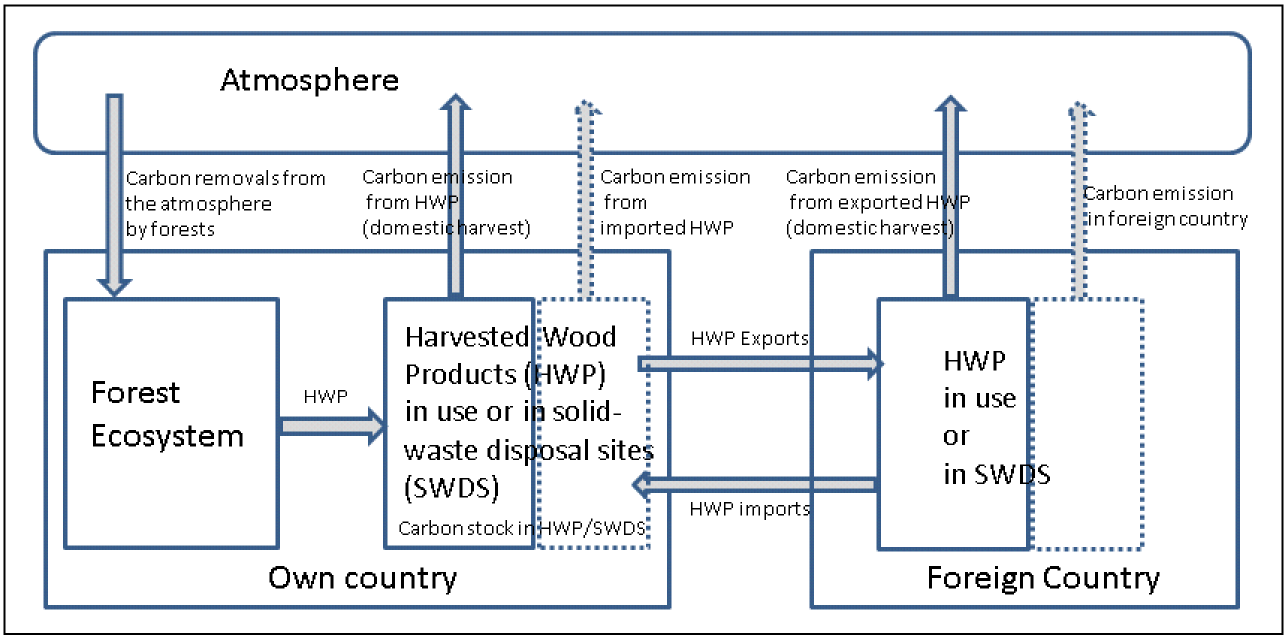
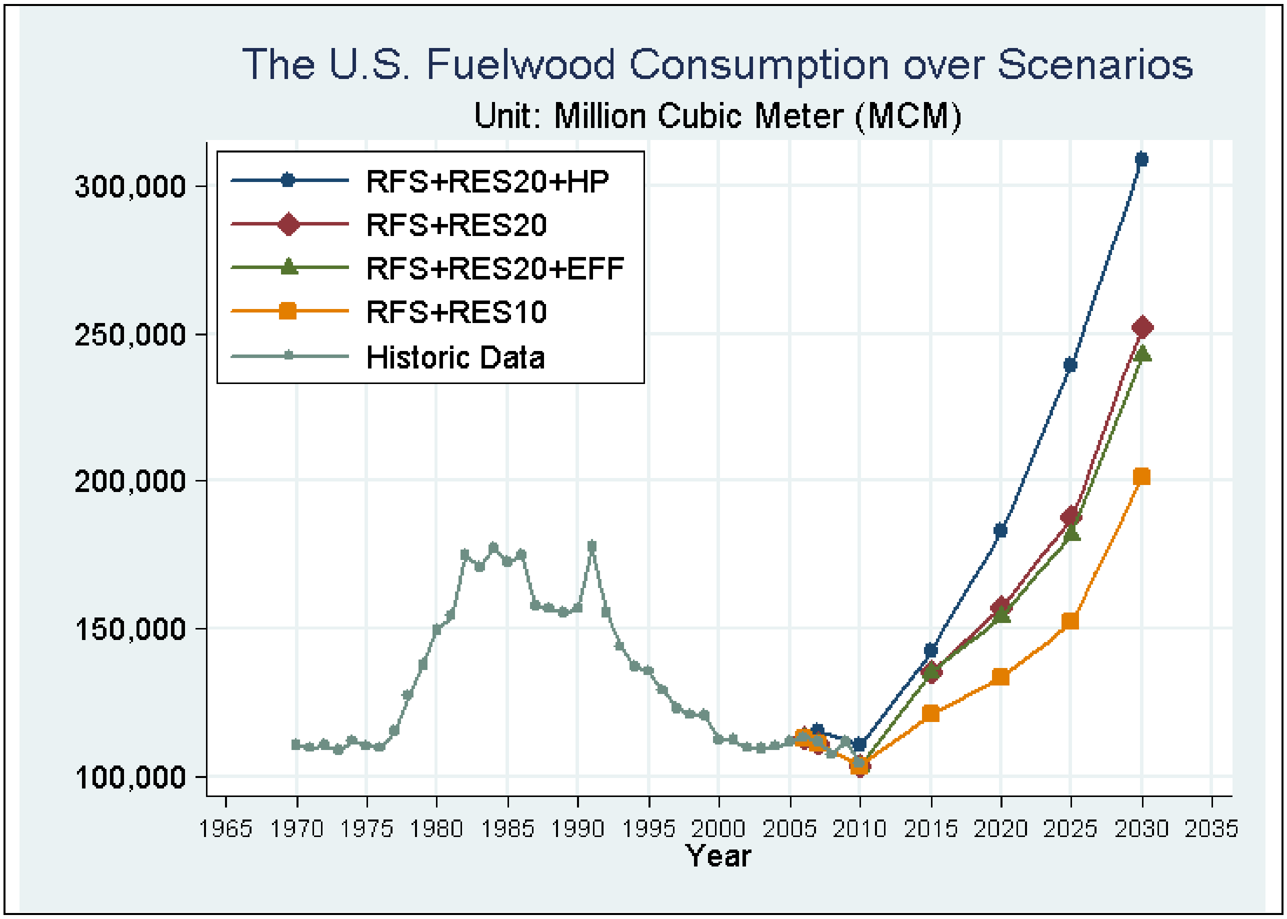
APPENDIX

<Figure 1. The U.S. carbon flows and stocks for HWP>

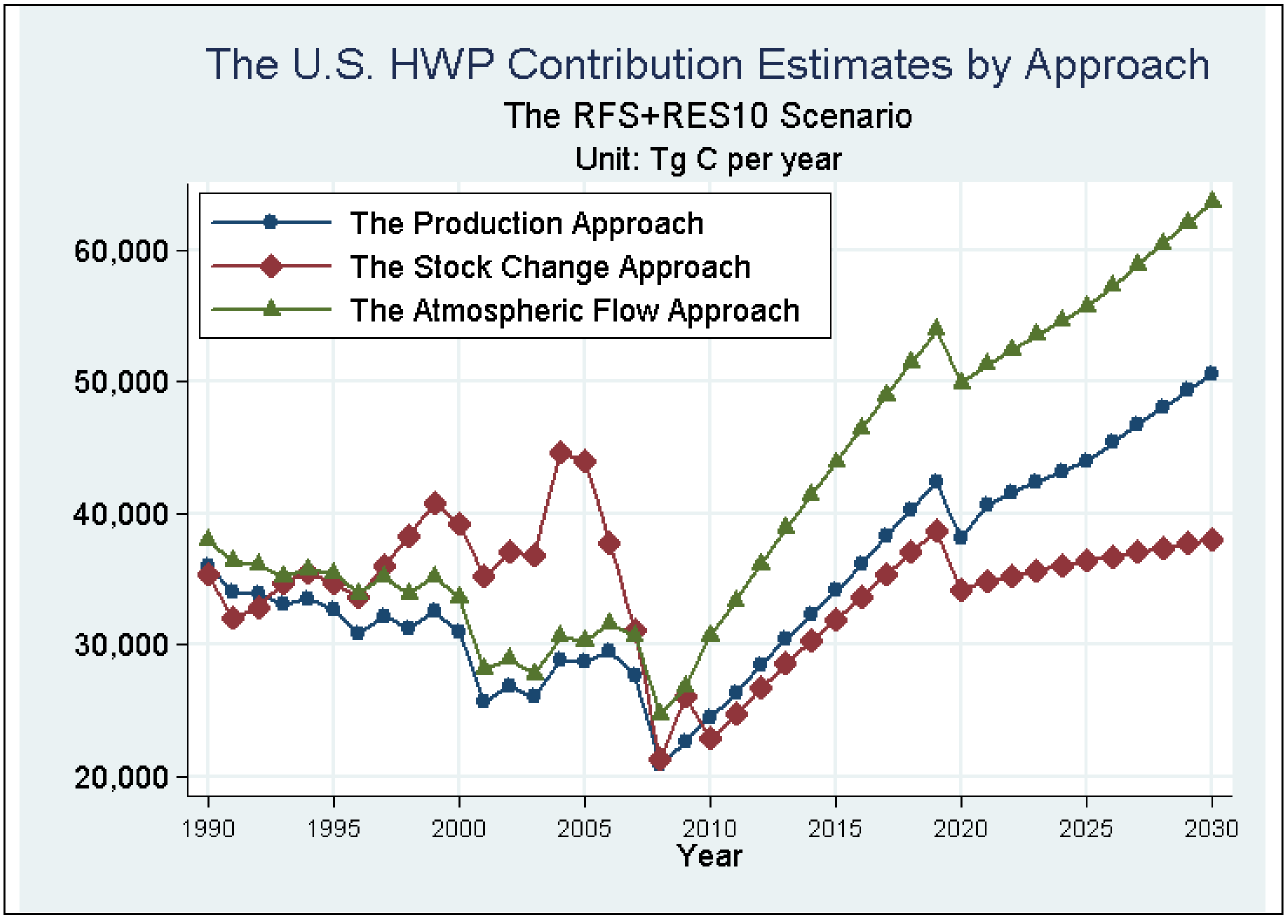


Dashed line indicates HWP from foreign countries.

<Figure 2. The U.S. fuel wood consumption over scenarios>



<Figure 3. The U.S. HWP Contribution estimates by approach in the RFS+RES10 Scenario>



<Table 1. Metric tons of carbon (Mg C) per unit of forest products[a]>

Forest product (l)	Metric tons Carbon per cubic meter[b] (β_l)	Product unit
Softwood Roundwood	0.26	million cubic meter
Hardwood Roundwood	0.29	million cubic meter
Softwood pulpwood	0.27	million cubic meter
Hardwood pulpwood	0.27	million cubic meter
Softwood Lumber	0.26	million cubic meter
Hardwood Lumber	0.29	million cubic meter
Softwood Plywood	0.28	million cubic meter
Hardwood Plywood	0.34	million cubic meter
Oriented Strandboard (OSB)	0.32	million cubic meter
Industrial Particleboard	0.29	million cubic meter
Fuelwood	0.29	million cubic meter
Other industrial roundwood	0.27	million cubic meter
Medium-Density Fiberboard	0.48	million cubic meter
Particleboard and Medium-Density Fiberboard	0.35	million cubic meter
Newsprint, Printing & Writing Paper, and Other Paper & Board	0.45	metric tonnes
Mechanical and Chemical Pulp	0.50	million cubic meter

[a]Sources – Skog (2008)
[b]Assumes 0.5t carbon per od ton wood and 0.43t C per od ton paper

<Table 2. The U.S. total fuel feedstock consumption projection in 2030 across scenarios>

	Historical Data	RFS+RES10 (baseline)	RFS+RES20+EFF	RFS+RES20	RFS+RES20+HP
Year	2006	2030	2030	2030	2030
% of fuel wood to the U.S. total primary energy consumption in 2030		1.30%	1.60%	1.80%	2.50%
Total fuel feedstock consumption[a]	113,255	167,511	214,347	226,841	308,511
Increment ratio (2006 ~ 2030)		47.91%	89.26%	100.29%	172.40%
Change ratio to baseline projection in 2030			27.96%	35.42%	84.17%

[a]Unit: Million cubic meter

<Table 3. The U.S. production projection by products in 2030 across scenarios>

	Historical Data	RFS+RES10 (baseline)	RFS+RES20+EFF	RFS+RES20	RFS+RES20+HP
Year	2006	2030	2030	2030	2030
Lumber & veneer	108,488	108,079	131,822	135,934	139,884
OSB & non-structural panels	27,599	37,890	33,516	30,281	23,016
Wood pulp	53,211	38,551	36,184	34,362	28,755
Paper & Paperboard	82,892	82,448	77,827	76,204	72,964
Total fuel feedstock	113,166	115,700	298,895	349,622	515,707
Source from:					
Harvest residue	0	0	94,976	104,503	132,443
Mill fuel residue	67,283	63,823	76,647	79,096	80,320
Mill fiber residue	0	1,463	24,531	30,935	42,781
Forest fuelwood	45,884	38,755	46,184	50,829	67,188
Pulpwood	0	11,658	56,558	84,259	192,904
SRWC	0	0	0	0	71.5

Unit: Million cubic meter

<Table 4. HWP Contribution under the RFS+RES10 and EPA (2011)>

year	The Production Approach				The Stock Change Approach				The Atmospheric Flow Approach			
	The RFS+RES10		EPA (2011)		The RFS+RES10		EPA (2011)		The RFS+RES10		EPA (2011)	
1990	35.98	(131.93)	35.94	(131.77)	35.39	(129.77)	35.35	(129.62)	37.98	(139.27)	37.75	(138.42)
1991	34.01	(124.69)	33.75	(123.76)	31.97	(117.22)	31.73	(116.35)	36.33	(133.21)	35.85	(131.44)
1992	33.84	(124.08)	33.76	(123.79)	32.80	(120.25)	32.72	(119.99)	36.13	(132.46)	35.90	(131.63)
1993	33.03	(121.11)	32.92	(120.71)	34.69	(127.19)	34.58	(126.81)	35.15	(128.87)	34.86	(127.82)
1994	33.50	(122.84)	33.41	(122.50)	35.53	(130.28)	35.44	(129.95)	35.73	(131.02)	35.42	(129.88)
1995	32.63	(119.64)	32.29	(118.41)	34.68	(127.15)	34.36	(125.98)	35.46	(130.01)	34.91	(128.01)
1996	30.89	(113.27)	30.61	(112.22)	33.64	(123.34)	33.37	(122.34)	33.89	(124.27)	33.41	(122.50)
1997	32.16	(117.91)	32.00	(117.34)	35.99	(131.98)	35.85	(131.44)	35.17	(128.97)	34.74	(127.38)
1998	31.19	(114.36)	31.11	(114.07)	38.20	(140.08)	38.13	(139.81)	33.86	(124.15)	33.46	(122.70)
1999	32.53	(119.28)	32.48	(119.08)	40.80	(149.62)	40.75	(149.41)	35.15	(128.89)	34.73	(127.34)
2000	30.93	(113.40)	30.79	(112.90)	39.18	(143.67)	39.05	(143.19)	33.55	(123.01)	32.81	(120.30)
2001	25.69	(94.18)	25.49	(93.45)	35.18	(128.99)	34.99	(128.28)	28.17	(103.30)	27.35	(100.27)
2002	26.81	(98.29)	26.78	(98.18)	37.01	(135.72)	36.99	(135.62)	28.89	(105.93)	28.13	(103.13)
2003	26.00	(95.34)	25.86	(94.83)	36.85	(135.11)	36.71	(134.61)	27.80	(101.94)	27.05	(99.19)
2004	28.88	(105.90)	28.73	(105.33)	44.61	(163.57)	44.46	(163.02)	30.62	(112.28)	29.76	(109.12)
2005	28.72	(105.30)	28.74	(105.38)	44.00	(161.35)	44.03	(161.43)	30.27	(110.99)	29.74	(109.03)
2006	29.55	(108.33)	29.61	(108.57)	37.73	(138.34)	37.79	(138.56)	31.58	(115.80)	31.14	(114.18)
2007	27.64	(101.36)	28.08	(102.97)	31.05	(113.84)	31.50	(115.49)	30.68	(112.48)	30.56	(112.06)
2008	20.85	(76.45)	22.39	(82.10)	21.25	(77.93)	21.38	(78.38)	24.71	(90.62)	25.71	(94.27)
2009	22.64	(83.03)	14.80	(54.25)	26.12	(95.76)	11.42	(41.89)	26.82	(98.36)	18.63	(68.30)
Average (1990 ~ 2009)	29.87	(109.53)	29.48	(108.08)	35.33	(129.56)	34.53	(126.61)	32.40	(118.79)	31.60	(115.85)

[a]Source: Table A-224 (EPA, 2006).
Unit: Tg C/ year.
Parentheses indicate a net removal of carbon from sequestration (Tg CO_2 equivalent per year).

<Table 5. HWP variables in terms of HWP Contribution by approach in the RFS+RES10 scenario>

	1990	1995	2000	2001	2002	2003	2004	2005	2006
The Production Approach									
Annual change of Carbon in HWP in use[a]	17.69	15.36	12.93	8.88	9.57	9.78	12.55	12.35	12.22
Annual change of Carbon in HWP in SWDS[b]	18.29	17.27	17.99	16.81	17.23	16.22	16.33	16.37	17.32
HWP Contribution[c]	35.98	32.63	30.93	25.69	26.81	26.00	28.88	28.72	29.55
Net removals from the atmosphere[d]	(131.93)	(119.64)	(113.40)	(94.18)	(98.29)	(95.34)	(105.90)	(105.30)	(108.33)
The Stock Change Approach									
Annual change of Carbon in HWP in use[e]	17.07	17.59	20.59	17.45	18.63	19.28	26.50	25.73	18.93
Annual change of Carbon in HWP in SWDS[f]	18.32	17.09	18.59	17.73	18.38	17.56	18.11	18.27	18.80
HWP Contribution[g]	35.39	34.68	39.18	35.18	37.02	36.85	44.61	44.00	37.73
Net removals from the atmosphere[h]	(129.77)	(127.15)	(143.67)	(128.99)	(135.72)	(135.11)	(163.57)	(161.35)	(138.34)
Tha Atmospheric Flow Approach									
Annual Imports[i]	12.68	16.71	22.43	22.98	24.60	25.96	31.65	31.71	25.49
Annual Exports[j]	15.27	17.49	16.79	15.97	16.48	16.92	17.66	17.98	19.34
HWP Contribution[k]	37.98	35.46	33.55	28.17	28.89	27.80	30.62	30.27	31.58
Net removals from the atmosphere[l]	(139.27)	(130.01)	(123.01)	(103.30)	(105.93)	(101.94)	(112.28)	(110.99)	(115.80)

2007	2008	2009	2010	2011	2012	2013	2014	2015	2015	2020	2025	2030
The Production Approach												
10.24	3.70	5.27	7.04	8.86	10.79	12.52	14.11	15.58	15.58	17.98	22.45	27.40
17.40	17.15	17.37	17.46	17.51	17.66	17.89	18.17	18.49	18.49	20.09	21.55	23.24
27.64	20.85	22.64	24.49	26.37	28.45	30.41	32.28	34.08	34.08	38.06	44.00	50.64
(101.36)	(76.45)	(83.03)	(89.81)	(96.67)	(104.30)	(111.50)	(118.36)	(124.95)	(124.95)	(139.57)	(161.34)	(185.67)
The Stock Change Approach												
12.56	3.38	7.93	4.97	6.93	8.92	10.68	12.27	13.73	13.73	14.99	16.33	17.10
18.49	17.87	18.19	17.90	17.78	17.77	17.84	17.97	18.15	18.15	19.16	20.06	20.94
31.05	21.25	26.12	22.86	24.71	26.69	28.52	30.25	31.88	31.88	34.15	36.39	38.04
(113.84)	(77.93)	(95.76)	(83.84)	(90.60)	(97.86)	(104.59)	(110.90)	(116.88)	(116.88)	(125.21)	(133.43)	(139.47)
Tha Atmospheric Flow Approach												
21.60	17.36	19.46	11.10	10.20	9.30	8.40	7.50	6.60	6.60	3.77	2.43	1.61
21.23	20.82	20.17	18.88	18.82	18.75	18.69	18.63	18.57	18.57	19.52	21.72	27.21
30.68	24.72	26.83	30.65	33.33	36.14	38.81	41.37	43.84	43.84	49.90	55.68	63.64
(112.48)	(90.62)	(98.36)	(112.37)	(122.19)	(132.52)	(142.32)	(151.69)	(160.74)	(160.74)	(182.95)	(204.17)	(233.35)

[a] Products from domestic consumption; unit: Tg C/ year; $\Delta X(t)$ in Equation (6).

[b] Products from domestic consumption; unit: Tg C/ year; $\Delta\tilde{X}(t)$ in Equation (11).

[c] HWP Contribution under the Production Approach; unit: Tg C/ year; $\Delta X(t)+\Delta\tilde{X}(t)$ in Equation (16); row [a] + row [b].

[d] Net carbon sequestration under the Production Approach; unit: Tg CO_2 eq./ year; row [c]*(44/12).

[e] Products from domestic harvest; unit: Tg C/ year; $\Delta H(t)$ in Equation (9).

[f] Products from domestic consumption; unit: Tg C/ year; $\Delta\tilde{H}(t)$ in Equation (14).

[g] HWP Contribution under the Stock Change Approach; unit: Tg C/ year, $\Delta H(t)+\Delta\tilde{H}(t)$ in Equation (15) (row [e] + row [f]).

[h] Net carbon sequestration under the Stock Change Approach; unit: Tg CO_2 eq./ year, row [g] * (44/12).

[i] Annual imports of roundwood, chips, residue, pulp, and recovered paper; unit: Tg C/ year; $\sum_{l^*}^{L^*}\sum_{j}^{J}\beta_{l^*}T_{ji=\text{U.S.}l^*}$ in Equation (17).

[j] Annual exports of roundwood, chips, residue, pulp, and recovered paper; unit: Tg C/ year; $\sum_{l^*}^{L^*}\sum_{j}^{J}\beta_{l^*}T_{i=\text{U.S.}jl^*}$ in Equation (17).

[k] HWP Contribution under the Atmospheric Flow Approach; unit: Tg C/ year; in Equation (17); (row [a] + row [b] – row [i] + row [j]).

[h] Net carbon sequestration under the Atmospheric Flow Approach; unit: Tg CO_2 eq. / year, row [k] * (44/12).

<Table 6. The U.S. HWP Contributions by approach across the alternative scenarios>

	EPA (2011)		RFS+RES10 (baseline)		RFS+RES20+EFF		RFS+RES20		RFS+RES20+HP	
Year	2006		2030		2030		2030		2030	
Fuel wood Production[a]	113,166		201,187		242,696		252,068		308,671	
The Production Approach										
HWP Contribution[b]	29.61	(108.57)	50.64	(185.67)	51.28	(188.04)	51.44	(188.63)	51.79	(189.89)
Rate of change (2006 ~ 2030)			71.01%		73.19%		73.74%		74.90%	
The Stock Change Approach										
HWP Contribution[b]	37.79	(138.56)	38.04	(139.47)	38.03	(139.43)	38.03	(139.43)	38.30	(140.45)
Rate of change (2006 ~ 2030)			0.65%		0.62%		0.62%		1.36%	
The Atmospheric Flow Approach										
HWP Contribution[b]	31.141	(114.18)	63.64	(233.35)	64.38	(236.08)	64.49	(236.47)	64.54	(236.66)
Rate of change (2006 ~ 2030)			104.36%		106.75%		107.10%		107.27%	

[a] Unit: Million cubic meter
[b] Unit: Tg C/ year
Parenthesis indicates net Carbon sequestration (Tg CO_2 eq. / year).