Assessment of Carbon Emission and Balance from Hardwood Lumber Processing in Central Appalachia, USA

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Abstract

This study assessed credit carbon emission and carbon balance from lumber processing of different size sawmills and its effect on the potential carbon offsetting capacity through wood product useful life. Data were obtained from a regional sawmill survey, public database and relevant publications. Credit carbon balance was statistically analyzed within the gate to gate life cycle inventory framework. Stochastic simulation of carbon emission and its impact on carbon balance and carbon flux from the lumber processing was carried out under different operational scenarios. The results showed that credit carbon balance from electricity consumption was significantly different among sawmills with different production levels and operation hours per week. Variation in carbon emission was also recognized due to different head saws, lighting types, and air compressors used at sawmills. Generated credit carbon balance in significant amount from energy consumption reduced carbon accountability of the lumber in useful life period at first order of decay of carbon. This credit carbon balance would also affect carbon disposition pattern in hardwood sawlogs. Substantial carbon flux occurred due to greater amount of energy consumption and exports of lumber would also reduce carbon accountability of lumber production. Carbon storage accountability of hardwood lumber and carbon flux during processing could be improved by using efficient equipment at sawmill and as well as appropriate mixture of electricity sources.

***Keywords*:** A. Carbon balance, B. Life cycle inventory, C. Sensitivity analysis, D. Energy consumption.

Introduction

Carbon (C) stocks of wood products are important in evaluating their potentials in greenhouse gas (GHG) mitigation (Brown et al. 1998, IPCC 2003). Carbon tracking in wood products requires knowledge of life cycle for realistic estimation and statistical representation of potential carbon contained in wood. Most estimates of C stocks and stock changes are based on indirect estimation models using hypothetical parameters (Harmon et al. 1994, Apps et al. 1999). One of the approaches to estimate C pools in wood products is accounting the amount of carbon expected to be stored in wood products and in landfills at the end of a 100-year period (Skog et al. 2004, Smith et al. 2006, Birdsey 2006). Estimation of C in wood products can start from the quantity of roundwood that is harvested, removed from the forest and available to primary processing for wood products in the mills (Birdsey 2006). Carbon emission estimation of wood products during their life time is affected by the decay rate and fraction of carbon allocated to long-lived products (Dias et al. 2005, Smith et al. 2006).

Lumber manufacturing involves different stage and different type of mechanical equipment that consume different energy sources. Mechanical equipment such as head saw and air compressors and sawmill management strategies such as production capacity and lighting bulbs, could have potential variation in carbon emission level from energy consumption. This type of variation in carbon emission “credit carbon” was overlooked in the previous studies of life cycle inventory (LCI) of wood product processing. Such carbon emission is also disregarded while accounting the carbon stored by the produced wood product in its useful life period. Therefore, it seems necessary to assess the carbon balance of hardwood lumber processing within the gate to gate life cycle inventory framework. The objectives of this study were to: (1) assess the carbon balance variation from energy consumption during hardwood lumber processing and (2) examine the effect of credit carbon in the carbon accountability of the product in its useful life period.

Methods

Methodological framework and system boundary. The debit and credit balance accounting principle was used to account carbon emission as greenhouse gas emission irrespective of other gaseous emission. The process of carbon storage begins with the green hardwood logs at log yard of sawmills and ends with the final product of planed dried sawn lumber within gate to gate life cycle inventory framework. The system boundary and the process unit were defined as described by the National Renewable Energy Laboratory Life Cycle Inventory (NREL 2010) database that covers the processing of green hardwood logs at sawmill, kiln drying of rough sawn hardwood lumber and planning of kiln dried sawn lumber. Data on lumber production, mill residue, energy consumption and energy efficiency practices in the Appalachian sawmills were obtained from a mail survey in 2010.

Carbon emission from energy sources. Carbon emission (Mg/TCM) from electricity consumption (MJ/TCM) was estimated using an average emission factor for mixed energy sources reported by the US Environment Protection Agency (USEPA 2010) on emission and generation resource integrated database (eGrid) for the regions of RFC WEST (WV & OH), RFC EAST (PA) and NYUP (NY) in 2004, 2005, and 2007. Carbon emission from the mixed energy sources such as fossil fuel, coal, oil and gas was assumed as an average of 0.17 kg/MJ (USEPA 2010). Carbon generated from energy sources, such as natural gas, propane, fuel #1, fuel #4 and fuel #6 was estimated using the national average of carbon dioxide coefficient reported by USEIA (2011). Similarly, carbon from diesel and motor gasoline was estimated based on emission facts by USEPA (2005). Energy gained from wood source was excluded assuming that it was substituted by residue generated from lumber processing at sawmill and to avoid double quantification of carbon stock. Other related carbon emission from electricity consumption (*EC*) from offsite generation and onsite generation and all energy sources (*ES*) used in lumber processing was based on a report CORRIM (Bergman and Bowe 2008).

Carbon emissions (Mg/TCM) from electricity consumption in lumber processing of difference size sawmill were simulated using known variance (normal likelihood) and assuming conjugate normal prior mean for 1000 times to examine the uncertainty of carbon emissions through Markov-chain Monte Carlo (MCMC pack) simulation in R. Scenario analysis of carbon emission from electricity source in eGRid sub region was carried out assuming coal, gas, oil and other fossil fuel are major source of electricity generation. The electricity generation share percentage of these four energy sources were proportioned to the total electricity required for the hardwood lumber processing.

Carbon in lumber and mill residue. Wood loss occurred during lumber processing was accounted as a percentage of carbon loss from green log volume at sawmill yard. An average of 296 kg of carbon was contained in one cubic meter of logs for the central Appalachian mixed hardwood species (Saud 2011). A similar value of 307kg/m^3 was used for carbon in per unit of roundwood in the northeast region (Skog and Nicholson 1998). In hardwood lumber processing, volume shrinkage changed from 1.46 m^3 of green lumber to 1.37 m^3 of dried lumber (Bergman and Bowe 2008). Therefore, we assumed 315kg/m^3 carbon contained in per unit volume of planed dried lumber (Saud 2011, Bergman and Bowe 2008). Mill residues such as chips and sawdust reported in green tons were assumed to contain 50% moisture, and were then converted to dry tons (Siau 1984). Carbon content of mill residue was assumed to be similar to hardwood logs with mixed species (296 kg/m^3). Carbon emission from residue was termed as carbon emission with and without energy capture. Emitted with energy capture refers to carbon emission from wood in relation to energy generation and emitted without energy capture refers to carbon emission through combustion or decay without concomitant energy recapture.

Analysis of impact of carbon emission ($C_{emission}$) from electricity at sawmills and from other energy sources on the fraction of carbon (j) in lumber ($FC_{lum_{i,j}}$) from lumber production year (i) to over its useful life period of 100 years (n) was conducted. For this carbon pay off period (*PP*) (Eq. 1) was estimated, the pay off period starts at the time when the amount of carbon emitted/credit carbon balance from lumber processing equivalent to the fraction of carbon remained in lumber at year *i*. This payoff period was estimated under half-life scenario at first order of decay rate of carbon and the carbon disposition rate based on hardwood lumber and industrial roundwood in the northeast region respectively (Smith et al. 2006). In the first year of lumber production year, i equal to 1 and j equals to zero because the fraction of carbon loss from produced lumber is zero (Smith et al. 2006). Similarly, carbon emission from an average of all energy consumption at sawmills was analyzed for the carbon disposition pattern in sawlogs for *n*-years period.

Carbon flux from lumber processing was also analyzed considering the carbon emission from energy consumption, export of lumber and carbon loss from mill residues at sawmill. Four different scenarios of carbon flux (*CF*) from energy ($CE_{enerery}$), export of lumber (CF_{export}) and lumber production FC_{lum}, for 100-year period (*n*) were analyzed. Cumulative carbon balance in lumber (CCB_{lumber}) (Eq. 2), cumulative carbon emission from energy (CCE_{energy}) (Eq. 3), cumulative carbon flux from export (CCF_{export}) (Eq. 4) were used to estimate cumulative carbon flux ratio (*CCFR*) (Eq. 5). The base case includes carbon flux from average energy consumption at sawmill and average export of the lumber from sawmill. Other scenario cases of carbon flux were (1) from export and all energy source consumption (2) from export and 25% reduction in carbon emission or in all energy source consumption, and (3) export and 50% reduction in carbon emission or all energy source consumption.

$$PP = C_{emission} = \sum_{i=1,\, j=0}^{n=100} FC_{lum_{i,j}} \quad (1)$$

$$CCB_{lumber} = \sum_{i=1,\, j=0}^{n=100} (FC_{lum_{i,j+n}} + FC_{lum_{i+1,j+n}} + \cdots\cdots\cdots + FC_{lum_{i+n,j+n}}) \quad (2)$$

$$CCE_{energy} = \sum_{i=1}^{n=100} CE_{energy_i} \quad (3)$$

$$CCF_{export} = \sum_{i=1}^{n=100} CF_{export_i} \quad (4)$$

$$CCFR = \frac{CCF_{export} + CCE_{energy}}{CCB_{lumber}} \quad (5)$$

Where, *PP* means carbon pay off period, $C_{emission}$ means carbon emission, $FC_{lum_{i,j}}$ means the fraction of carbon (*j*) in lumber from lumber production year (*i*); CCB_{lumber} means the cumulative carbon balance in lumber, *CF* means carbon flux, $CE_{enerery}$ means carbon flux from energy, means carbon flux from export of lumber, FC_{lum} carbon flux from lumber production; CCE_{energy} means cumulative carbon emission from energy, CE_{energy_i} means carbon flux from energy emission in year i; CCF_{export} means cumulative carbon flux from lumber export, CF_{export_i} means carbon flux from lumber export in year i; *CCFR* means cumulative carbon flux ratio.

Results and Discussion

Carbon emission from electricity consumption. Sawmills were operated with an average of 35, 40, 43 hours per week with one shift in small sawmills (SSM), medium sawmills (MSM) and large sawmills (LSM), respectively. Similarly, yearly operation weeks averaged 48 for SSM and 50 weeks for both MSM and LSM. The electricity consumption rate was different among sawmills with different production capacity (Table 1). The mean carbon emission from electricity consumption was 23.96, 11.03 and 0.87 Mg/month for LSM, MSM, and SSM, respectively. Therefore, carbon emission from lumber processing was 9.01, 17.51, and 9.40 Mg/TCM in LSM, MSM, and SSM, respectively. The lower carbon emission in LSM might attribute of the higher lumber production level with the use of efficient electric motor in the larger sawmills. Significant difference existed in carbon emission from electricity ($p=0.0047, F=6.6928$), among operating hours per week ($p=0.004523, F = 6.2198$), and among lumber production levels per week ($p=0.0001, F=125.44$) of different sawmills.

Table 1. *Descriptive statistics of lumber production and electricity consumption.*

Sawmill type	Lumber production (m^3/month)			Electricity (MJ/month)		
	Mean	Min	Max	Mean	Min	Max
SSM	152.16	4.72	377.56	18,943	1,800	79,200
MSM	822.29	424.75	1,415.84	318,337	5,796	1,025,640
LSM	2,624.03	2,123.76	3,539.61	584,431	400,000	1,168,358

Carbon emission and energy capture. To produce 1000 m^3 of lumber, a total of 2290 m^3 of green roundwood is required and almost 64% of the volume is turned into wood residues (NREL 2010, Bergman and Bowe 2008). From survey result, approximately, 316.5 out of 680.13 metric tons of wood carbon is deposited in major mill/wood residues such as sawdust, chips and slabs during lumber processing. Few sawmills produced slabs in each sawmill size group. An average of 637.5, 422.50, and 383.22 green Mg/TCM of chips and an average of 220.86, 262.50, and 232.71 green Mg/TCM of saw dust were generated in SSM, MSM, and LSM. It corresponds to an average of 212.5, 140.8, and 127.7 Mg/TCM of carbon from chips and 73.5, 87.5, and 77.6 Mg/TCM of carbon form sawdust in SSM, MSM, and LSM. Thus, an average of 286, 228.3, and 205.3 Mg/TCM of carbon were emitted with and without energy capture correspondingly from SSM, MSM, and LSM in the form of wood residue, respectively.

Onsite carbon emission due to energy capture was greater from the combustion of chips than sawdust (Fig. 1). Chips recaptured greater amount of carbon at sawmills when it was used either for heating or fueling purpose such as 91.1 Mg/TCM at SSM and 71 Mg/TCM at LSM, while carbon emission from sawdust was 18.4 Mg/TCM at SSM and 13.68 Mg/TCM at LSM, respectively. This recaptured carbon as energy source released into the atmosphere at year zero of the lumber production. In the study area, timber product output data of 2001 and 2006 showed that an average 92% of carbon is emitted from mill residue as energy source (USDA FS 2010). In addition, such energy captures could account to supply 1.5% of the total energy consumption in U.S. (Perlack et al. 2005).

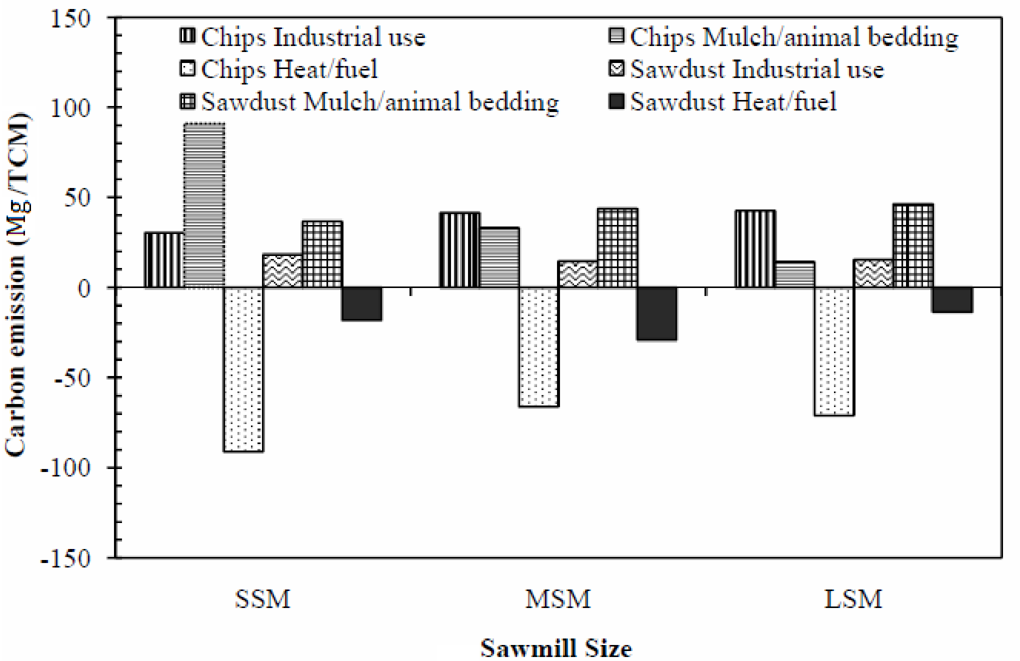

Figure 1. Carbon emissions with and without energy capture process from sawmill.

Industrial use of chips and sawdust was another source of carbon emission from energy capture process. Carbon emission from chips was greater in LSM and MSM while it was greater in SSM and LSM from sawdust. They were utilized either to generate heat or produce different short lived wood products, i.e. pulp and paper, pallets and barn that could lengthen carbon emission period. Carbon emission without energy captured from chips was significantly greater in SSM (91.1 Mg/TCM) and it was greater in LSM (46.54 Mg/TCM) from sawdust. Such carbon emission from the use of residue either for mulching purpose on the farm or for animal bedding lagged the carbon release time into the atmosphere than used for heat/fuel. This type of carbon emission, without energy capture, accounts for 8% of the total carbon from mill residues (USDA FS 2010). Mill residues used for industrial purpose or farm purpose would be supportive to lengthen wood carbon life and increase carbon stock, as wood product with short life does.

Energy efficient equipment. It was found based on our survey that MSM (13.9%) and LSM (8.3%) had upgraded efficient techniques to increase avoided carbon emission per unit of lumber production, but SSM didn't. However, every sawmill group had normally used efficient electric motor and had achieved usually 80-90% efficiency level (Table 2). The efficiency level was related to the use of different efficient techniques such as head saw, lighting bulb and air compressor. Sawing of logs was carried out from the use of head saw such as band (38.1%), circular saw (45.22%) and both saws (16.7%). Lighting used in sawmills varied from fluorescent bulb (53.8%), incandescent bulbs (17.9%) and both bulbs (28.2%). Similarly, sawmills used conventional air compressor (45.7%) and/or high efficiency screw drive air compressor (45.7%) and both compressors (8.6%).

Table 2. *Descriptive statistics of the efficient technique utilization in sawmill types.*

Efficient Techniques	SSM	MSM	LSM	Total
Upgraded for energy efficient	0.0%	13.9%	8.3%	22.2%
Efficient electric motor utilization	12.2%	36.6%	22.0%	70.80%
Efficiency level				
80-90%	13.6%	27.3%	9.1%	50.0%
91-94%	4.5%	13.6%	18.2%	36.4%
>94%	4.5%	4.5%	4.5%	13.6%

Carbon balance in lumber production. The credit carbon balance accounts for 2.9, 5.5, and 2.8% of the net debit carbon balance of lumber (316.5 Mg/TCM) at the zero year of lumber production in the SSM, MSM, and LSM, respectively. Effect of this credit carbon balance was not significant in the net debit carbon balance of lumber under half-life scenario up to 100 years (Fig. 2a). However, net debit carbon balance could be affected after the useful life period of 100 years, i.e. at beginning of the time period, and lumber would be discarded from their use purpose and disposed at landfills. The low credit carbon balance could be attributed to low electricity consumption by sawmills and it could be higher when other fossil fuels were consumed.

Estimated total carbon emission from electricity consumption (*EC*) was 28.5 Mg/TCM and it accounts for 9% of the carbon stored in the processed lumber. In 100 years of useful life period, it bisects at year 79 and becomes equivalent to the amount of carbon remained in lumber at first order of decay rate (Fig. 2b). The payoff period (*PP*) begins after year 79 and it reduced the carbon accountability period of lumber in its useful life by 21%. In addition, 35.91 Mg/TCM of credit carbon balance generated from all energy sources (*ES*) accounted for 11.35% of the carbon balance in lumber. It bisects at year 67 and shortens carbon accountable period of the lumber almost by 33% (Fig. 2b). Hence, carbon emitted from lumber after the bisected point year would be equivalent to the amount of carbon debt created by credit carbon balance from lumber processing. The higher the debt carbon balance is, the early *PP* and consequently lower the carbon accountability in useful life period of the lumber would be. This *PP* would vary depending on the hardwood tree species used for lumber processing because the carbon content value among tree species differs.

Lumber processing of 1000 m^3 sawlogs contains an average of 680 metric tons of carbon. This carbon disposition pattern of sawlogs was significantly affected by the generated credit carbon balance. An average credit carbon balance generated from all energy sources in lumber processing at sawmills only affected the carbon disposition pattern of sawlogs in landfills (Fig. 2c). The generated carbon credit balance from only *EC* affected the period of carbon disposition pattern of sawlogs and the *PP* begins for fraction of carbon in use either at later 11 years or for fraction of carbon in landfills at first 3 years (Fig. 2d).

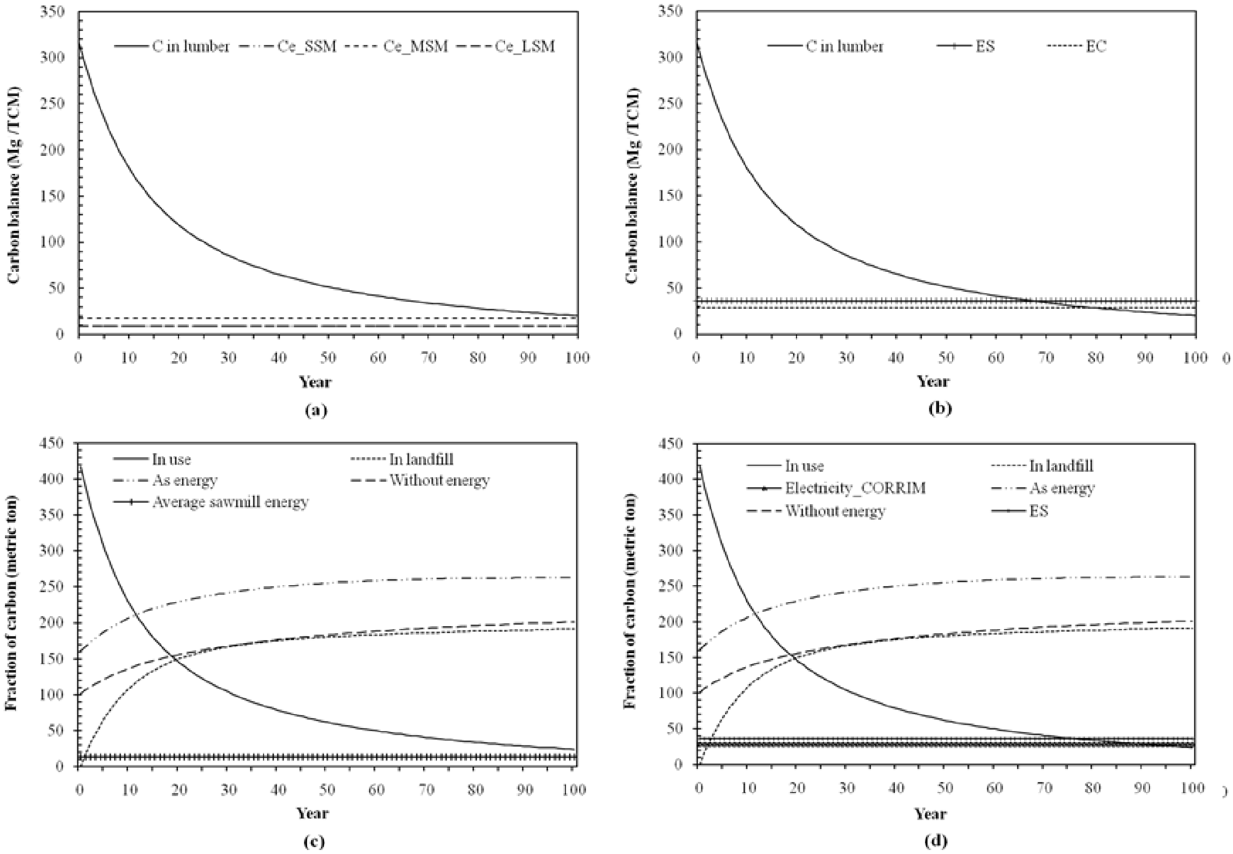

Figure 2. Effect of credit carbon balance in carbon balance of lumber and fraction of carbon disposition in sawlogs at 100 years period: (a) and (b) carbon balance by carbon emission level and energy consumption, (c) average sawmill energy consumption, and (d) electricity consumption (*EC*) all energy sources (*ES*).

Carbon flux from lumber processing. More carbon was emitted in the lumber processing mainly from the generated mill residues. Carbon flux from mill residues was 96.56 Mg/TCM as energy capture, 55.3 Mg/TCM as industrial use, 88.51 Mg/TCM as farm manure, and 123.8 Mg/TCM as others. The use and no use of mill residues increases the atmospheric carbon level from zero year of lumber production to 5 years depending on what purposes they are used for (Karjalainen et al. 2002, Skog 2008, Sharma 2010). Carbon flux was also instigated by export of the lumber. An average of 6.7% of lumber produced was exported and it reduced carbon stock of lumber production and place to 93.3% of available accountable wood carbon stock in the region.

The consequence of cumulative carbon emission from energy sources was observed in the cumulative carbon balance at the first order of carbon decay in the lumber production cycle of 100 years. In the base case, the CCF_{lumber} (21.1 Mg/TCM) was 57.2% higher than the cumulative carbon emission from electricity (13.1 Mg/TCM) at sawmills for 100 years of lumber production (Fig. 3a). However, the combined carbon flux from the electricity and export did not affect carbon stored in the produced lumber because the *CCFR* ranged from 0.12 to 0.42 from year zero to year 100.

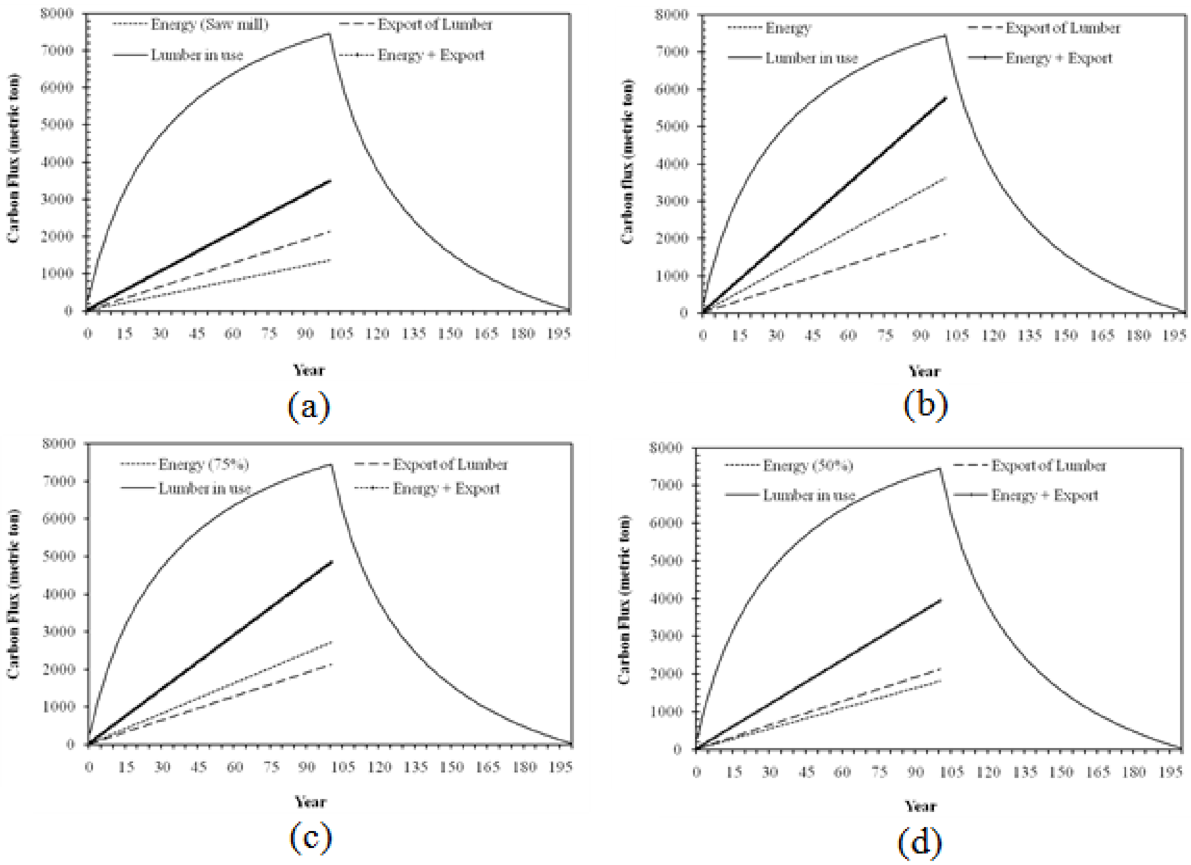

Figure 3. Atmospheric carbon fluxes from hardwood lumber processing in 100 years: (a) average electricity consumption at sawmills (b) all energy source consumption, (c) 25% reduction in all energy source consumption, and (d) 50% reduction in all energy source consumption.

The cumulative carbon emission from the total energy consumption and export of lumber could affect the cumulative carbon balance in lumber (Fig. 3b). In this case, the *CCFR* from the all CCE_{energy} energy source consumption (ES) (104.57 GJ/TCM) and CCF_{export} was 0.19 to 0.77 for the hardwood lumber production years of 0 to 100. Thus, at the end of 100 years of production period, only 23% of the CCB_{lumber} would be available to account as the net debit carbon balance. Therefore, a great amount of carbon emission would affect the CCB_{lumber} production period and it would also discount such credit carbon balance at later years of the wood product life.

When 25% of the carbon emission from all energy source consumption was reduced, the *CCFR* would range from 0.16 at zero years to 0.65 at 100 years (Fig. 3c). In this situation, 45% of the carbon in the lumber would be available to account as net CCB_{lumber} at 100 years. Similarly, if reducing 50% of carbon emission from all energy source consumption (Fig. 3d), it could have the similar effect as carbon flux created from electricity and export by sawmills.

Carbon emission under different energy sources. Since a great amount of electricity (607.2 GJ/TCM) is required for lumber processing (Bergman and Bowe 2008), it increases the atmospheric carbon level significantly. Generating such amount of electricity from natural gas would emit carbon equivalent to an average carbon emission level from the current electricity generation from the mixed energy sources in the Appalachian region. Estimated carbon emission amount was 39.2 Mg/TCM for other natural gas source, 32.8 Mg/TCM for coal source, 28.5 Mg/TCM for current mixed source, 25.6 Mg/TCM for natural gas, and 16.5 Mg/TCM for oil source (Fig. 4a). Carbon emission from single source of electricity generation such as fossil fuel would be greater followed by coal. Therefore, the electricity generated from an appropriate mixture of energy sources could help avoid certain amount of credit carbon balance. The base case represents electricity generation from the mixed energy sources in central Appalachian region, scenario 1 represents RFC WEST, and scenario 2 represents RFC EAST, and scenario 3 NYUP (Fig. 4b). The credit carbon balance was 30.9 Mg/TCM, 29.5 Mg/TCM, 27.2 Mg/TCM, and 32.8 Mg/TCM for the base case, scenario 1, scenario 2 and scenario 3, respectively.

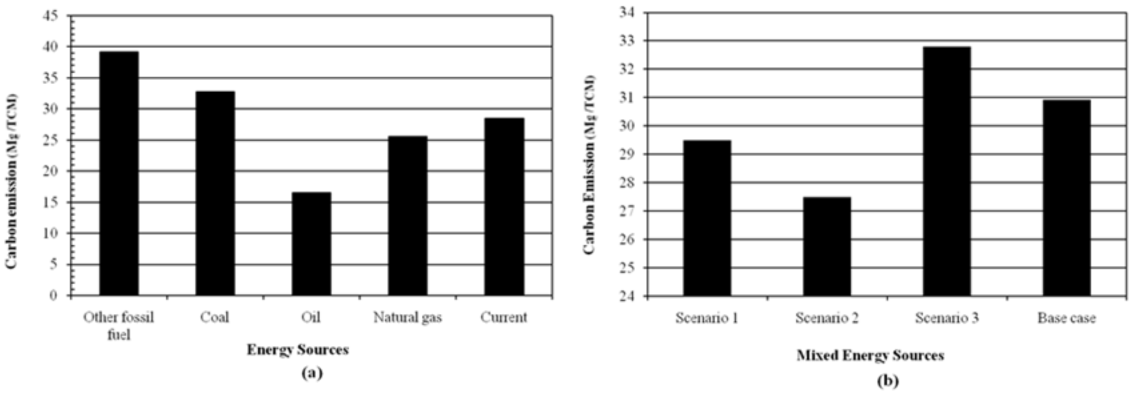

Figure 4. Carbon emissions from electricity generation during hardwood lumber processing using: (a) single energy sources and current average, and (b) mixed energy sources.

Conclusions

Carbon emission from electricity consumption during processing per unit of lumber varies depending on sawmill size. This variation would be coupled from electricity generation sources and available equipment at sawmills during processing per unit of lumber. The random mixed effect of the available equipment such as head saws types, lighting blubs types and air compressors types also influence the credit carbon balance of a sawmill. Such carbon emission could be avoided to some extent if using energy efficient motors and equipment at sawmill, which would be beneficial in abating carbon credit balance. Though carbon stored in produced lumber increases carbon stock of the wood carbon pool and magnifies humans' carbon mitigation efforts, carbon flux occurs due to significant wood loss during sawmill processing. Not all carbon loss from mill residues would be immediately recaptured as energy source and released into the atmosphere. Significant amount of mill residues would be help lengthen carbon release time period from zero to 5 years through industrial use, or uses as mulching and farm bedding.

Carbon balance in lumber would be affected by the credit carbon generated during its processing. Carbon disposition pattern of sawlogs would also be affected greatly by this credit carbon balance. If accounted carbon emission that occurred from process of the wood product gain processing and product use such as: harvesting of timber, transportation of lumber and its uses in house construction or any other purposes, the debt carbon for lumber would attribute more. The potential measures to neutralize carbon debt could reforest the harvested area timely to pay off the carbon debt and it would also increase debit carbon balance benefit from wood. Carbon emission from electricity consumption could be minimized by using energy source that has lower carbon coefficient. Thus, appropriate mixed energy sources in the region would be helpful to minimize carbon emission from electricity consumption at sawmills. Carbon flux from export of lumber also decreases the carbon accountability of the cumulative lumber production in years. The greater the carbon flux ratio from energy and export is, the lower the carbon accountability of the produced lumber would be.

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