A Life Cycle Assessment of Forest Carbon Balance and Carbon Emissions of Timber Harvesting in West Virginia, USA

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Abstract

Forest management activities such as harvesting and transportation emit carbon dioxide (CO_2) and these emissions are often overlooked when estimating the carbon benefits from forests and forest products. This study assessed the net aboveground biological carbon balance of mixed hardwood forests in West Virginia and carbon emissions from the use of fossil fuels in timber harvesting. A life cycle inventory framework of 'cradle to gate' combined with Monte Carlo stochastic simulation was used to analyze the forest carbon balance and emissions from year 2000 to 2009. The results showed that the annual carbon balance of the forests per hectare was not significantly affected by carbon loss from the volume of removal, fire and limited dead trees, unless the number of dead trees or harvesting intensity are increased. Additionally, it was found that average carbon emissions from fossil fuel consumption were 5.06 ± 0.90 metric tons per thousand cubic meters (Mg/TCM) of timber produced using a manual harvesting systems and 6.84 ± 1.22 Mg/TCM when using a mechanized harvesting system. The forest carbon displacement rate during timber harvesting was affected largely by the hauling process compared to felling, processing, skidding and loading processes. Species group, forest type, and harvest intensity influenced forest carbon displacement rates and carbon in harvested timber. Uncertainty of carbon emissions from fuel consumption and forest carbon displacement rate was also related to hauling distance, payload size, forest type, and machine productivity.

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

Introduction

Increasing concentration of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the atmosphere inspires development of strategies to mitigate climate change impact (Petit et al. 1999; Vannien and Makela 2004; IPCC 2006). One climate mitigation strategies is to focus on increasing the amount of carbon stored in forests or forest products and quantifying the carbon (C) budgets of forest stands (Raupach et al. 2007; Hennigar et al. 2008). Forests, being the largest terrestrial carbon reservoir (Dixon et al. 1994), may increase or decrease carbon stock using different management strategies and practices (Richard et al. 1997).

An assessment of forest carbon that includes timber harvesting intensity level, forest growth rates, dead trees and forest fire loss is necessary to characterize the net forest carbon balance of the existing forest stock. Similarly, consideration of different forest types, harvesting systems, harvesting residue extraction systems, and truck types, would be useful to illustrate the variation of carbon emission rates that could potentially occur during the timber harvesting process. Thus, it is imperative to analyze and quantify forest carbon balances and variation in carbon emissions traceable to fossil fuel consumption in the process of evaluating forest harvesting and management practices. Therefore, the objective of this study was to evaluate the net carbon offset of central Appalachian hardwood forests under current management and harvesting strategies using life cycle inventory (LCI) approach to address current and future sustainability in terms of carbon balance and carbon accumulation potential of forests. The specific objectives were to (1) assess the forest carbon balance of mixed hardwood forests in West Virginia, and (2) analyze the carbon emissions from fossil fuel combustions of harvesting systems in West Virginia.

Materials and Methods

Data. Natural regenerating forests in West Virginia representing typical central Appalachian forests sequester a vast quantity of atmospheric carbon. This carbon capture serves to offset carbon emissions from fossil fuel consumption in transportation and industrial process. Forestland covers almost 76% of the state and 71% of the forests are privately owned (Milauskas and Wang 2006; USDA FS 2010). Data on forest growth and removals, and harvesting production and costs obtained from published literature and public archives were used, within a cradle to gate (sawmill gate) life cycle inventory framework, following inventory data collection rules (ISO 2006) and good practice guidance for forestry practices (IPCC 2006). The system boundary encompassed harvesting systems that include fuel consumption in terms of felling, processing (topping and delimbing), skidding, loading, and hauling to a sawmill. Site regeneration factor was not included in the boundary. We selected a thousand cubic meter (TCM) volume of harvested hardwood timber as the base functional unit in harvesting system analysis.

Timberland data were obtained from an online Forest Inventory and Analysis database (FIA) maintained by USDA Forest Service (USDA FS 2010). Annual growing stock, annual removal, annual mortality (dead and fire), and annual growth of the forest tree species group were categorized by species groups. Net volume of live trees above 12.7cm (>5 inches) diameter at breast height (dbh) was included in carbon analysis in regard to commercial uses of these trees for either pulp or structural purposes. Mixed hardwood (MHRD) species were considered for analysis and it comprise almost 95% of the forest area. Inventory data on net volume of live trees and net volume of dead trees were available for 2000, 2004, 2005, 2006, 2007, 2008 and 2009. However, data on net growth volume and harvested volume were only available for the years of 2000, 2006, 2008 and 2009.

The green weight of harvested residue biomass ($BHres_i$) by species group ($i=1, 2, \ldots, 19$) was estimated in metric tons (Mg) using Eq.1. The product of harvested volume (Hv_i) is in m^3 and density is in green weight ($Dengwt_i$) in metric tons/m^3. It was assumed that branches and tops of a tree contains biomass equivalent to 29% extra of the total stem biomass in the Northeastern region (INRS 2007). It was also assumed that only 65% of wood residue can be economically extracted and are available due to technical and topographic feasibility (Perlack et al. 2005). However, these two parameters can be adjusted according to different biomass and operational conditions.

$$BHres_i = 65\% * (Hv_i * Dengwt_i * 29)/71 \qquad \forall\ i. \qquad (1)$$

Where, $BHres_i$ means the harvested residue biomass by species group i;
Hv_i means harvested volume by species group i;
$Dengwt_i$ means the density in green weight by species group i.

Forest Carbon Estimation. Carbon (CHv_i) of tree species (i) in harvested volume (Hv_i) was estimated using Eq. (2) by multiplying the harvested volume (Hv_i) by specific gravity (Sg_i) of the tree species at oven dry weight (Alden 1995) for each tree species and assuming a 50% of the total dry biomass weight is carbon (Smith et al. 2006). Similarly, carbon in wood residue ($CBHres_i$) was estimated at oven dry weight in Mg (Eq. 3). Carbon sequestered by dead trees (CB_D) was also estimated in metric tons. Since forest fire is another important factor for forest carbon loss, we estimated carbon emissions due to fires from 2002 to 2009 based on the data obtained from the West Virginia Division of Forestry (WVDOF 2010). Carbon loss from tree by forest fires (CB_F) was estimated in Mg ha^{-1} using an average estimated carbon content of current forest productivity per unit area times burnt forest area (ha).

Net carbon balance (C_{BL}), in metric tons per hectare ($Mg\ ha^{-1}$), of aboveground stem biomass was estimated (Eq. 4) by subtracting mean carbon removals CH_V, CB_D, and CB_F from existing carbon stock (CS) and adding by the mean carbon growth (CB_G). It was also examined for 200 years using Monte Carlo simulation to evaluate the uncertainty of forest carbon balance using mean (μ) and standard deviation (σ) and assuming a normal distribution of 1000 randomly generated numbers. Forest carbon displacement rate (DC_r) that determines reduction in carbon balance of harvested timber at the expense of carbon emission from fossil fuel consumption was calculated using Eq. (5). TCF_c is total carbon emission from fossil fuel consumption. However, the carbon sequestered by roots, branches, foliage and leaf litter on the forest floor was not considered in this study.

$$CHv_i=0.5*Hv_i*Sg_i \qquad \forall i. \tag{2}$$

$$CBHres_i=\frac{BHres_i}{Dengwt_i}*Sg_i*0.5 \tag{3}$$

$$C_{BL}=CB_G+(CS-CH_V-CB_D-CB_F) \tag{4}$$

$$DC_r=\frac{CHv_i-TCF_c}{CHv_i}*100\% \tag{5}$$

Where, CHv_i is the harvested timber carbon of species group *i* (Mg TCM^{-1}); Hv_i is the harvested volume of species group *i* (TCM); Sg_i represents the specific gravity of timber of species group *i*; $CBHres_i$ is the wood residue carbon in species group *i* (Mg TCM^{-1}); $BHres_i$ is the oven-dry weight of harvested residue biomass of species group *i* (Mg TCM^{-1}); $Dengwt_i$ is the density of biomass residue in green weight of species group i (Mg TCM^{-1}); C_{BL} is the net carbon balance (Mg Ha^{-1} for forest; Mg TCM^{-1} for harvested timber); CB_G is the mean carbon growth of forests (Mg Ha^{-1}); *CS* is the existing carbon stock (Mg Ha^{-1}); CH_V is the harvested timber carbon (Mg TCM^{-1}); CB_D is the carbon sequestered by dead trees (Mg TCM^{-1}); CB_F is the carbon loss from forest fires (Mg Ha^{-1}); DC_r is the carbon displacement rate (Mg TCM^{-1}); TCF_c is total carbon emission from fossil fuel consumption (Mg TCM^{-1}).

Carbon Emissions from Fuel Consumptions. C emissions were calculated for both manual and mechanized harvesting systems. Carbon emissions from diesel combustion (CD_c) and gasoline combustion (CG_c) were based on the carbon dioxide emission estimates by USEPA (2005). C emission from lubricant consumption (CL_c) was calculated using the method for industrial product and process by the IPCC (2006). The default carbon content of lubricant, 20.0 kg GJ^{-1} was used on a lower heating value basis. Using the principles outlined in the Good Practice Guidance of IPCC (2006) and by USEPA (2010), the total carbon emission (TCF_c) was estimated (Eq. 6) including C emissions from diesel (Eq. 7), lubricants (Eq. 8) and gasoline (Eq. 9) in timber harvesting, residue extraction, and timber and residue hauling process.

$$TCF_c=CD_c+CL_c+CG_c \tag{6}$$

$$CD_c=\left\{\sum_{k=1}^{n} Hv\left(\frac{\sigma_{mk}}{Pm_m}+\frac{\sigma_{ok}}{Pm_o}+\frac{\sigma_{pk}}{Pm_p}\right)+\frac{Hv}{pd}(d_g*2\gamma_q+d_p*\gamma_q)\right\}\alpha*\delta \quad \forall k. \tag{7}$$

$$CL_c=\left\{\sum_{k=1}^{n} Hv\left(\frac{\varphi_{mk}}{Pm_m}+\frac{\varphi_{nk}}{Pm_n}+\frac{\varphi_{ok}}{Pm_o}+\frac{\varphi_{pk}}{Pm_p}\right)+\frac{Hv}{pd}(d_g*2\,\partial_l+d_p*\partial_l)\right\}\beta*\delta \quad \forall k. \tag{8}$$

$$CG_c=\frac{\tau_{nk}}{Pm_n}*\eta*\delta \qquad \forall k. \tag{9}$$

Where, TCF_c is the total carbon emissions, CD_c is the carbon emissions from diesel combustion, CL_c represents carbon emissions from lubricant consumption, CG_c is the carbon emissions from gasoline combustion, *Hv* is the harvested volume (m^3) of timber, *k* is the k^{th} harvesting system (1 = manual, 2 mechanized); σ, φ, and τ are diesel, lubricant, gasoline consumption rates (liters per hour) of machine *m*, *n*, *o*, or *p* in harvesting system *k*; *Pm* is the productive machine hour of the involved machine *m, n, o*, or *p*; *pd* is the net payload (tons) of hauling truck; γ_q and ∂_q are diesel and lubricant consumption rates per km (liters/km) of hauling truck, *dg* is the gravel distance (km), *dp* is the paved distance in km, α is CO_2 emission (Mg) from diesel, β is CO_2 emission (tons) from lubricant, ŋ carbon emission (tons) from gasoline and δ is molecular weight of carbon (tons).

Sensitivity Analysis. In the base case scenario, carbon emissions were estimated for mixed hardwood species skidded for 500 meters distance and hauled 80 km (50 miles) using a 4-axle log truck with a 23 m^3 timber payload size for both mechanized and manual timber harvesting systems. Carbon displacement was analyzed for both harvesting systems and forest group type and residue extraction system. The carbon displacement rate was defined as the carbon emissions resulting from fossil fuel consumption in the harvesting system to the amount of carbon stored in the hauled timber. We categorized mixed hardwood tree species into three major forest type groups based on the national core field guide for North Central and Northeastern regions (USDA FS 2006). The selected major forest groups are (1) Oak-hickory including all oak species, hickory, black walnut and yellow-poplar, (2) Ash-cottonwood, and (3) Maple, beech, basswood and birch. Carbon emissions for mechanized and manual harvesting of mixed hardwood species were simulated to examine the uncertainty of carbon emissions using Markov-chain Monte Carlo (MCMC pack) simulation in R (statistical package). Annual carbon emissions from harvesting systems were proportioned to the system per unit production and simulated for 1000 runs under normal likelihood assumptions.

Results and Discussion

Forest Carbon Balance. During the period 2000 to 2009 in West Virginia, the average annual net volume of standing mixed hardwood forests is 689 ± 30.16 million cubic meters (MCM) with mean carbon stock of 46.76 ± 2.06 Mg ha^{-1}. Annual average additions to forest carbon stocks have been significantly different over the years (p = 1.430e-09) probably due to different growth in volume and removal through harvest and fire. Annual growth in volume of live trees has increased annual carbon accumulation (increase in forest carbon stock) with carbon stock additions also significantly different over the years (p = 0.001386). The annual tree growth added 1.09 ± 0.19 Mg ha^{-1} of C to the existing carbon stock as a statewide average. Annually, 2.6 ± 0.44 million tons (Mt) of C stored in trees were removed through harvesting from timberland with an average removal of 0.16 ± 0.03 Mg ha^{-1} during the period 2000 to 2009. This is equivalent to a removal rate of 44.89 ± 1.69 Mg ha^{-1} for those areas harvested. The mean carbon stock and carbon removed were significantly different among tree species groups. For example, yellow-poplar accounted for an average of 11% of the timberland stock but it constituted an average of 20% of the annually harvested timber volume in West Virginia. Annually, forest fires cause 0.21 ± 0.03 Mg of C loss stored in timberland and it resulted in an average of 0.05 ± 0.02 Mg ha^{-1} carbon loss during the period 2000 to 2009. Since only a small amount of forest carbon loss occurred due to forest fire, it would not significantly reduce net forest carbon balance. An annual carbon loss from net dead trees is 28.63 ± 15.06 Mg with an average of 6.35 ± 3.09 Mg ha^{-1}. Though a large amount of carbon loss occurred from dead trees, carbon release time in atmosphere would be lagged by the time period required for wood decay. Normally a period of 20 years is required to release carbon from dead trees (Janisch and Harmon 2002).

Simulation of forest growth for the next 100 years showed annual additions to carbon stocks ranging from 0.63 to 1.69 Mg ha-1 (Fig. 1a). The existing carbon balance from 2000 to 2009 would be 41.32 ± 4.11 Mg ha^{-1}. However, the forest carbon balance per hectare would not significantly different from the carbon loss per hectare in coming years because annual forest growth per hectare was attributed to the harvested timber volume and volume loss due to forest fire (Fig. 1b). If we limit the harvesting volume at current rate rather than hectare basis, then the carbon loss trends from forest area would be minimum. Therefore, the continuation of timber harvesting at the current mean annual harvest rate based on hectare would create large gap between carbon balance and carbon loss at constant removal and would be helpful to increase carbon balance through a slight variation in annual carbon accumulation might influenced by dead trees (Fig. 1b). However, this would not be possible in practice because of the increasing demand of wood and wood products. Thus, if we increased current harvesting intensity (volume) by 5% and kept constant for consecutive five years and repeated this process for 100-years period to meet the increasing wood demand, we found that a significant amount of carbon stock would be created and more atmospheric carbon would be sequestered in the forests.

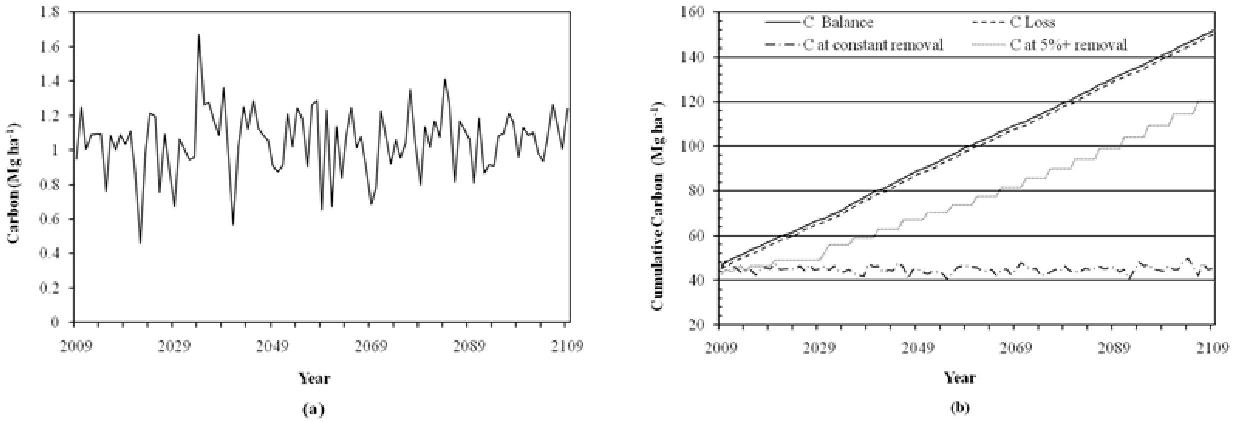

Figure 1. Predicted trends of carbon growth and carbon balance for 100 years:
(a) Carbon accumulation rate per hectare. (b) Cumulative carbon balance from stock and current carbon timber removal rate with the growth rate, constant timber volume removal rate and 5% increment in removal rate at consecutive five years period.

Carbon Emissions from Timber Harvesting and Transportation. Carbon emission rates from consumption of fossil fuel was 5.06 ± 0.90 Mg TCM^{-1} using manual harvesting systems and 6.84 ± 1.22 Mg TCM^{-1} using mechanized harvesting systems with a hauling distance of 80 km or less. Mean carbon emission level from mechanized and manual harvesting systems was not significantly different ($p = 0.058$) at 95% confidence level. It could be attributed to the similar fuel consumption and productivity rates for loading and hauling in both harvesting systems. Annual carbon emission was directly proportional to timber volume harvested. Carbon emission in both harvesting systems was lower compared to the average carbon content level (296 kg m^{-3}) of timber harvested that is consistent with the carbon content of (307 kg m^{-3}) for hardwood round logs in the Northeast region (Skog and Nicholson 1998).

Mean carbon emission of combined diesel and gasoline consumption did not differ significantly ($p = 0.106$) while it was significantly different from lubricant consumption ($p = 0.031$) between mechanized and manual harvesting systems. It was 6.06 and 4.61 Mg TCM^{-1} from combined diesel and gasoline consumption, 0.65 and 0.45 Mg TCM^{-1} from lubricant consumption for the mechanized and manual harvesting systems, respectively. In carbon emission level from both harvesting systems, hauling process contributed greater percentage of carbon emission from diesel and gasoline consumption (Table 1). It was followed by felling and skidding in mechanized harvesting system, whereas it was followed by skidding and loading process in manual harvesting system. It was also found that skidding process contributed greater percentage of carbon emissions from lubricant consumption in both harvesting systems.

Table 1. C emissions from fossil fuel due to harvesting hardwood species by harvesting function.

Harvesting	Manual harvesting system		Mechanized harvesting system	
function	Diesel (C %)	Lubricant (C %)	Diesel (C %)	Lubricant (C %)
*Felling	2.61	0.68	24.47	26.23
Processing	-	-	1.64	0.36
Skidding	27.19	83.08	21.65	61.99
Loading	22.71	4.41	16.90	3.10
Hauling	47.48	11.84	35.34	8.32

*Felling in manual harvesting consumes gasoline and topping and delimbing are also associated with felling process.

Carbon Displacement from Forest to Sawmill. Carbon stored in standing trees can be displaced from timberland to sawmill or processing facilities at the expense of carbon emissions from fossil fuel consumption of timber harvesting system. In the base case scenario of mechanized harvesting, the forest carbon displacement rate was 2.31% of the C stored in harvested timber, while it was 1.71% of the C stored in the harvested timber using manual harvesting system. This variation in forest carbon displacement was due to higher carbon emission of using mechanized harvesting system. As hauling distance increased, the carbon displacement rate also increased (Fig. 2a and 2b). It was 4.37% or 3.77%, respectively, for hauling up to 320 km using mechanized harvesting or manual harvesting system. Therefore, longer hauling distance could indirectly decrease the accountability of carbon balance of the harvested timber to some extent.

Approximately 188.5 m^3 (24.8 green Mg ha^{-1}) of logging residue was estimated from harvesting 1000 m^3 of mixed hardwood forests and it contains an average of 56 Mg of carbon. In the base case, payload number was 8, and forest carbon displacement rate was 0.83% and 1.1% of the carbon stored in logging residue using either a cable skidding system or a grappler skidding system, respectively. This difference was due to higher fuel consumption rate of using grapple skidder in residue extraction. The difference would be greater when hauling for a longer distance, i.e., 1.9% using cable skidder and 2.2% using grappler skidder for hauling up to 320 km (Fig. 2c and 2d). The forest carbon displacement rate varied among forest types (Fig. 2c and 2d) at for different hauling distances. This variation was due to green weight of unchipped residue that limits truck payload size. For example, available residue was 175.02, 147.97, and 153 green metric tons and carbon in wood residue was 55, 52, and 60 Mg for Oak-hickory, Ash-cottonwood and Maple-birch forest group respectively. If the truck payload size is 20 metric ton, then the payload numbers would vary for each forest group, and resulting the hauling cycle number changes for each forest type and fossil fuel consumption rate.

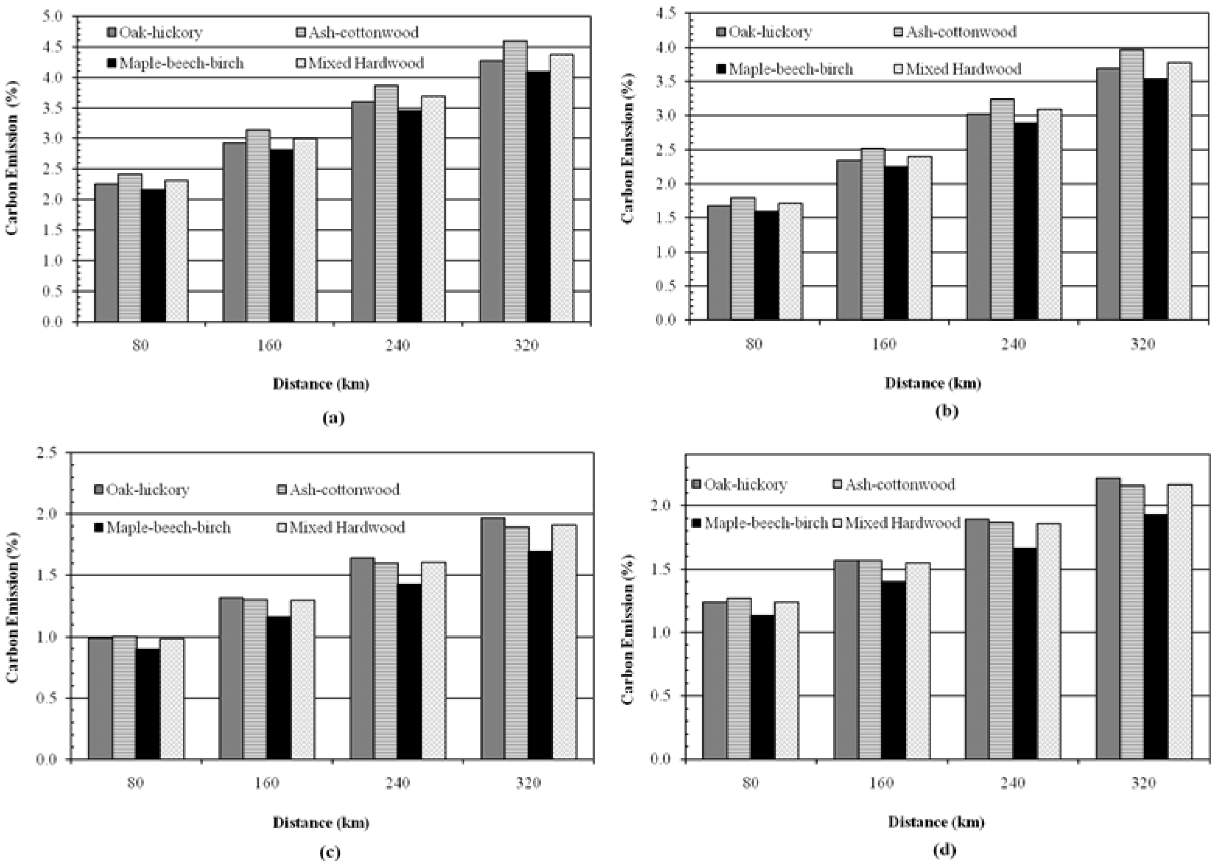

Figure 2. Carbon displacements of four different forest type from the timber harvesting systems and the generated residue extraction system. (a) and (b) timber harvesting under mechanized and manual harvesting systems. (c) and (d) residue extracting under cable and grappler skidding systems.

Sensitivity Analysis and Uncertainty of Carbon Emission. Carbon emission increased with skidding distance (Fig. 3a). It was increased from 0.19-0.47 Mg TCM^{-1} for grappler skidder and from 0.18-0.27 Mg TCM^{-1} for cable skidder when skidding distance changed from 300 to 1,000 m. The amount of carbon emission varied with hauling truck types. In the base case of 80 km hauling distance, the carbon emission amount was approximately the same for all five types of trucks. However, when hauling distance increased up to 320 km, it was found that carbon emission per unit volume of timber transported using a single axle truck was greater than using other truck types (Fig. 3b). A single axle truck has a relatively smaller payload and the similar cycle time though it consumes less fuel compared to other trucks. The use of a single tandem truck (4 axles) or a semi-tractor-trailer (5 axles) would be beneficial in minimizing carbon emissions for hauling a longer distance.

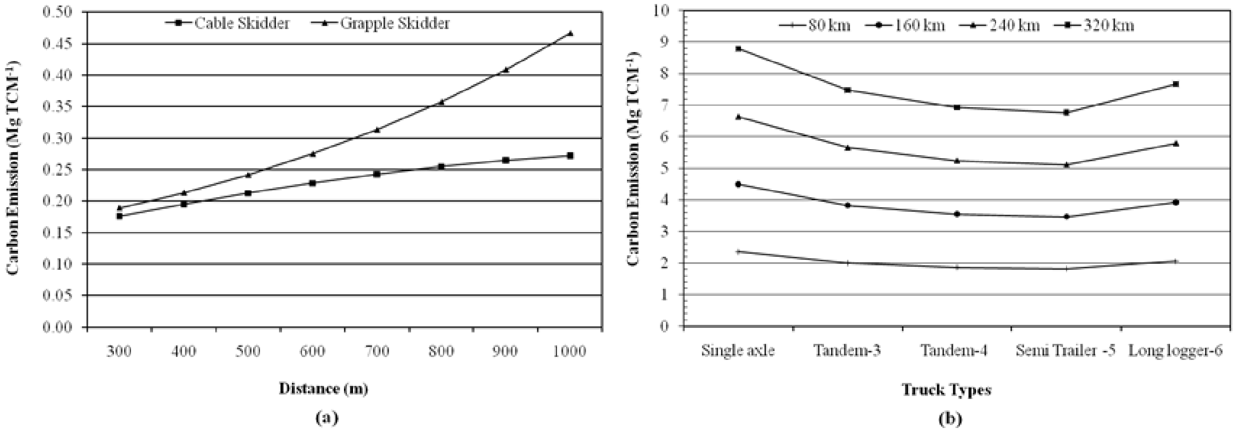

Figure 3. Carbon emission variations during skidding and hauling of mixed hardwood species: (a) by skidder types and skidding distance (meters) and (b) by truck type and hauling distance (km).

Conclusions

Forest carbon removal due to harvesting, fire and limited dead trees does not significantly impair the existing forest carbon stock in West Virginia. However, an increase in the number of dead trees or harvesting intensity could reduce the net carbon balance of timberland. Considering rotation age of natural mixed hardwood forests with slight increase in harvesting intensity would increase forest carbon stock and undermine carbon emissions from fossil fuel consumption of timber harvesting. Such practices would have healthy impacts on carbon stock for timberland and neutralize minor natural depreciation of carbon from fire loss and dead trees.

Natural regeneration in forests, as applicable in the central Appalachian region, entails no fossil fuel consumption in seedling production and plantation and thus results in zero carbon emission level from mechanized instruments. Although mechanized harvesting system emits more carbon into the atmosphere than manual harvesting system, the mean carbon emission does not differ significantly between these two systems. The amount of carbon emissions from fossil fuel consumption due to harvesting is considerably lower than the carbon stored in harvested timber and logging residue. Among harvesting functions, hauling presents a greater effect on carbon emission compared to felling, skidding, topping, delimbing and loading. Hauling distance and truck payload size are the two primary factors that influence carbon emissions, forest carbon displacement rate, and carbon balance in harvested timber. The uncertainty of carbon emissions and carbon balance of harvested timber depends on harvested timber volume of different forest types and hourly production and fuel consumption of machines in harvesting systems.

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