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

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Outline

- Introduction
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Introduction

- Increasing concentration of carbon dioxide (CO2) and other greenhouse gases (GHGs) in the atmosphere inspires development of strategies to mitigate climate change impact.

- 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.

- Forests management under sustainable principles has a biological foundation with inputs and outputs that can be incorporated into life cycle analysis (LCA).

- 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.

Objectives

- Assess the forest carbon balance of mixed hardwood forests in West Virginia.
- Analyze the carbon emissions from fossil fuel combustions of harvesting systems in West Virginia.

Methods

- Data
- Forest Carbon Estimation
- Forest Harvesting and Fuel Consumption
- Carbon Emissions from Fuel Consumptions
- Sensitivity Analysis

Methods(cont'd)

- Data

➢ 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 and good practice guidance for forestry practices.

➢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 (Fig. 1).

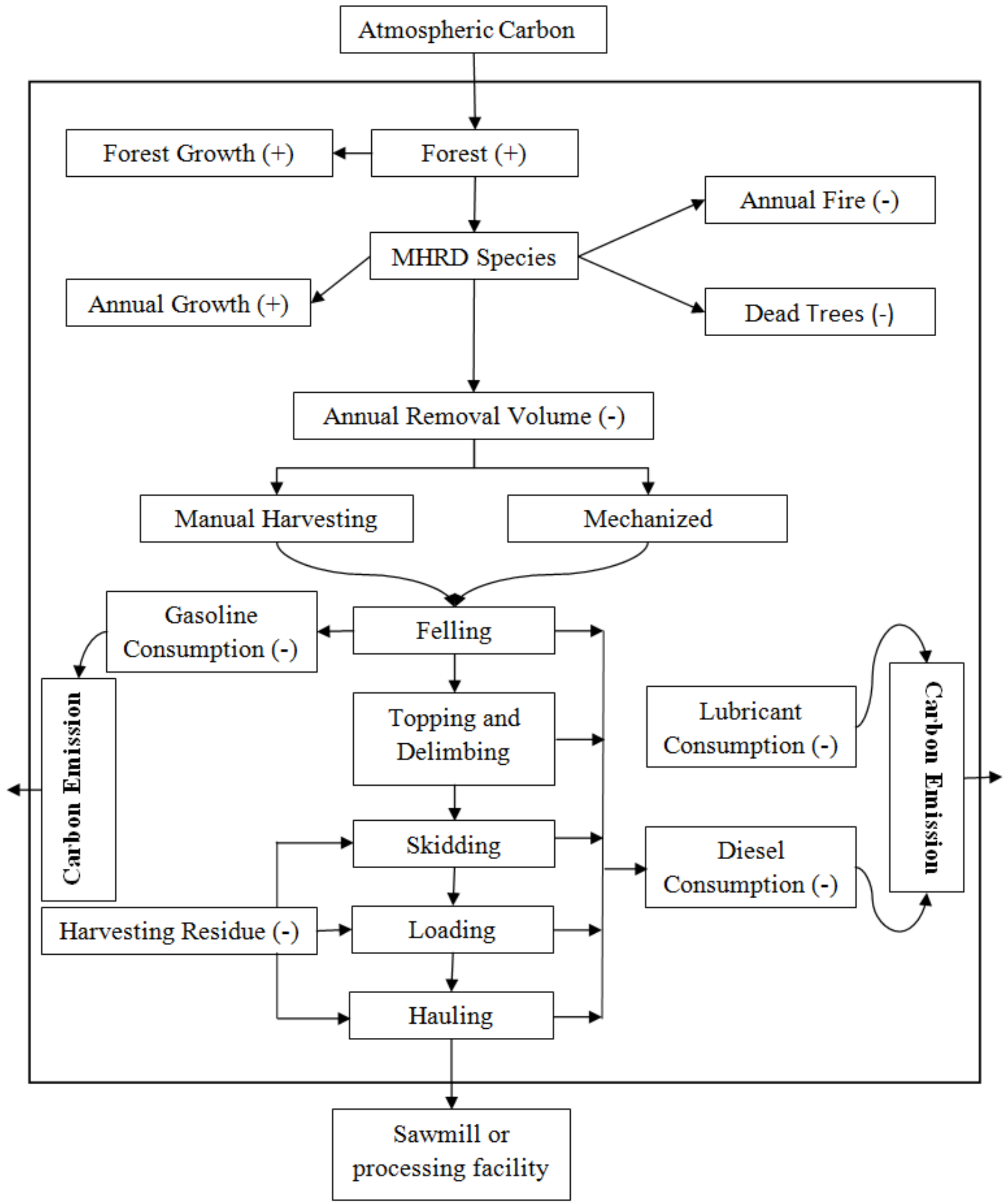


Figure 1. Life cycle inventory framework and system boundary.

Methods(cont'd)

- Timberland data were obtained from an online Forest Inventory and Analysis database (FIA).

- 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.

$$BHres_i = 0.65 * (Hv_i * Dengwt_i * 29)/100 \qquad \forall\, i. \qquad (1)$$

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

Methods(cont'd)

- Forest Carbon Estimation:

$$CHv_i = 0.5 * Hv_i * Sg_i \quad (2)$$

$$CBHres_i = \frac{BHres_i}{Dengwt_i} * Sg_i * 0.5 \quad (3)$$

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

$$DC_r = \frac{CHv_i - TCF_c}{CHv_i} * 100\% \quad (5)$$

Methods(cont'd)

- Forest Harvesting and Fuel Consumption:
  - Manual and mechanized harvesting systems are the two most commonly used systems in the central Appalachian region.
  - Data on machine utilization, fuel consumption, and productivity for harvesting were taken from a previous study by Wang et al. 2004.

Methods(cont'd)

- Carbon Emissions from Fuel Consumptions:

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.

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

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

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

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

Methods(cont'd)

- Sensitivity Analysis:

- In the base case scenario, carbon emissions were estimated for mixed hardwood species skidded for 500 meters distance and hauled 80 km using a 4-axle log truck with a 23 m^3 timber payload size for both mechanized and manual timber harvesting systems.

- 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).

- Sensitivity analysis of carbon emissions from timber harvesting and carbon displacement rate was conducted according to different **skidding distances**, **hauling truck type**, **hauling distance**, and **payload size**.

Results and Discussion

- Forest Carbon Balance:
  - 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 metric tons per hectare (Mg ha^{-1}).
  - 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}.

Results (cont'd)

- 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.
- 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}.
- 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.2a).
- However, the forest carbon balance per hectare would not significantly different from the carbon loss per hectare in coming years (Fig. 2b).

Results (cont’d)

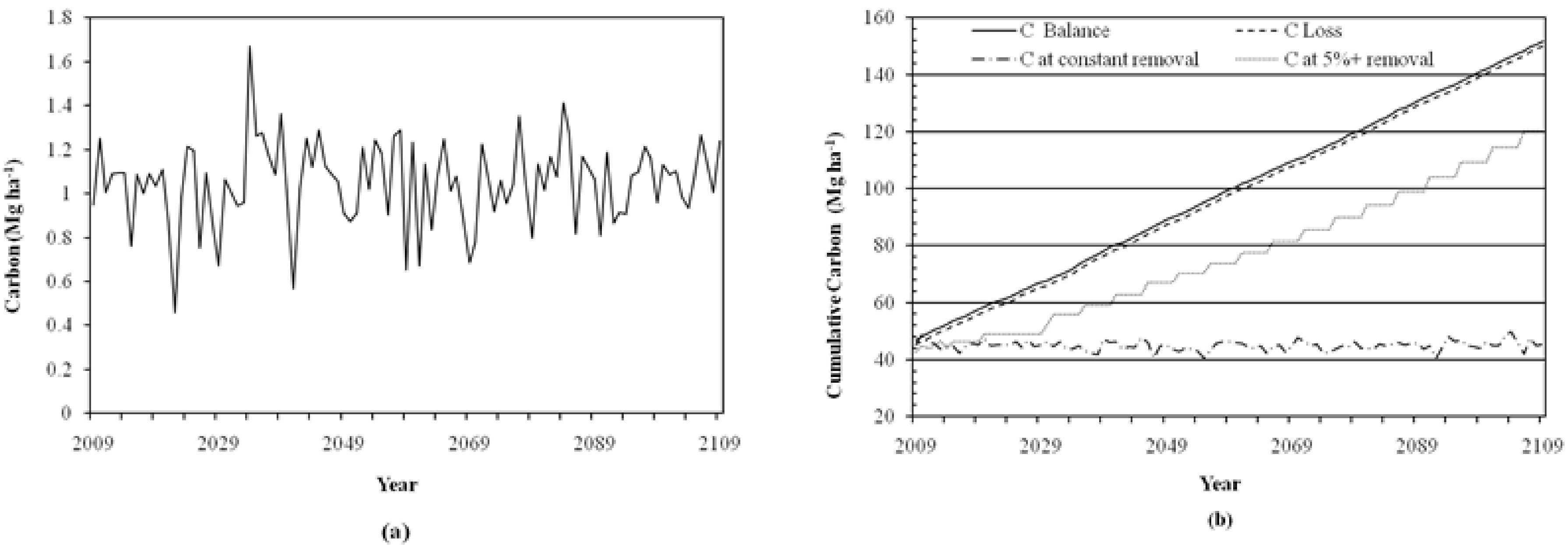


Figure 2. Predicted trends of carbon growth and carbon balance for 100 years of mixed hardwood forests in West Virginia:
(a) Carbon accumulation rate per hectare. (b) Cumulative carbon balance from stock and current carbon timber removal rate with the growth rate, constant timber volume removal rate and 5% increment in removal rate at consecutive five years period.

Results (cont'd)

- Carbon Emissions from Timber Harvesting and Transportation:
  - Carbon emission from consumption of fossil fuels was estimated at 5.06 ± 0.90 Mg TCM^{-1} using manual harvesting system and 6.84 ± 1.22 Mg TCM^{-1} using mechanized harvesting system.

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

Harvesting function	Manual harvesting system		Mechanized harvesting system	
	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.

Results (cont'd)

- Carbon Displacement from Forest to Sawmill:

- 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.

- As hauling distance increased, the carbon displacement rate also increased (Fig. 3a and 3b).

- The forest carbon displacement rate varied among forest types (Fig. 3c and 3d) at for different hauling distances.

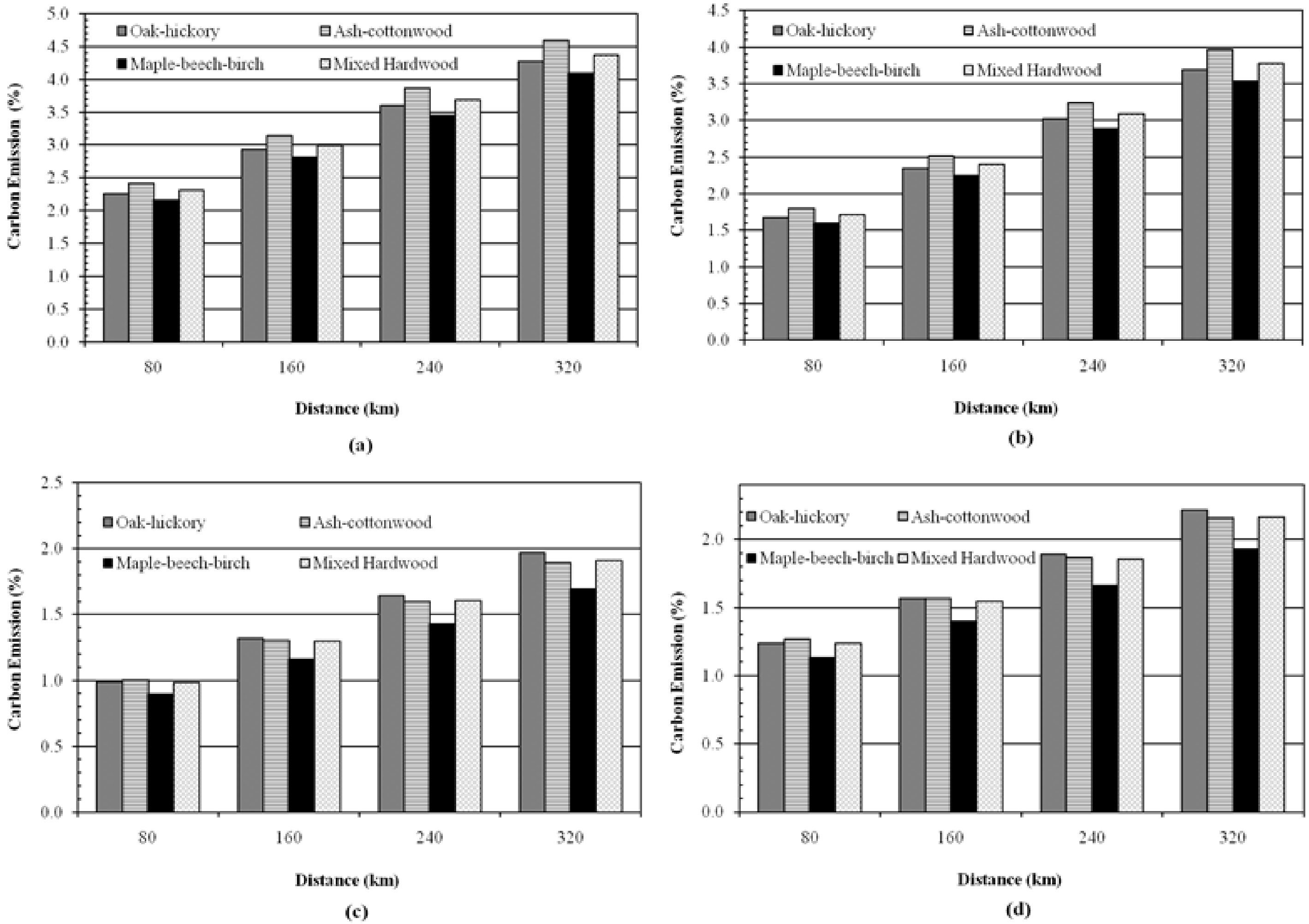


Figure 3. Carbon displacements of four different forest types by timber harvesting systems and generated residue extraction system: (a) and (b) timber harvesting using mechanized and manual harvesting systems; (c) and (d) logging residue extraction using cable and grappler skidding systems.

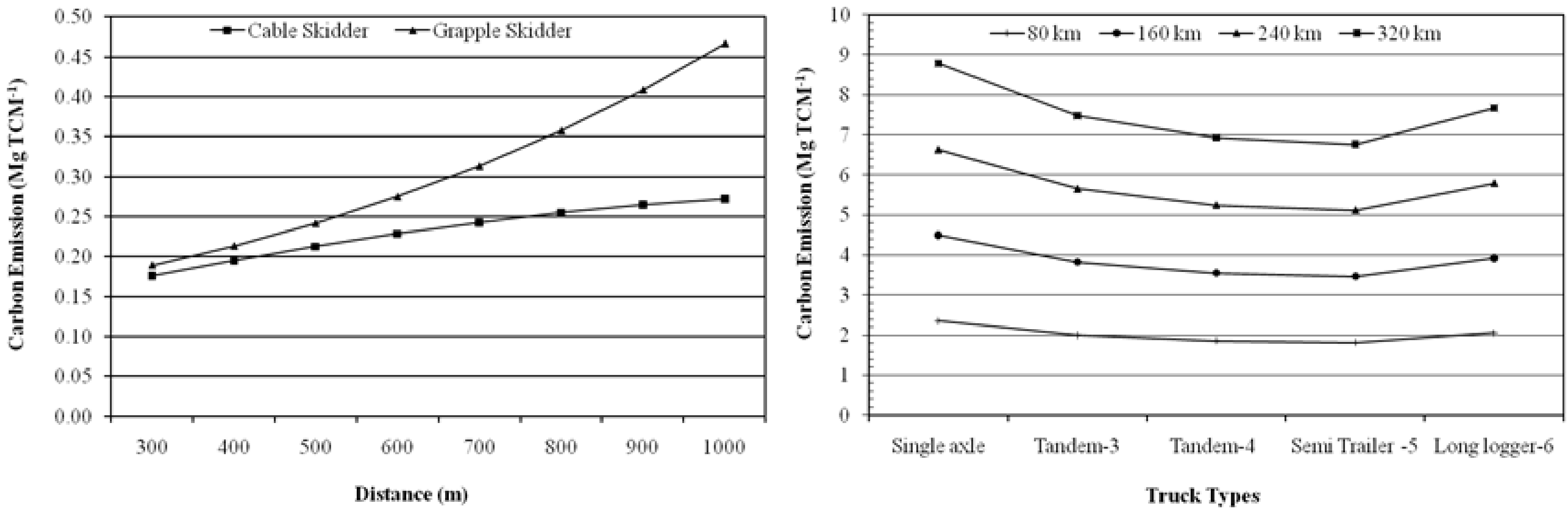
Results (cont'd)

- Sensitivity Analysis and Uncertainty of Carbon Emission:

  - Carbon emission increased with skidding distance (Fig. 4a). 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.

  - 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. 4b).

Results (cont'd)



(a) (b)

Figure 4. 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).

Results (cont'd)

For mechanized harvesting, the mean carbon emission was **6.87 ± 0.56** Mg TCM^{-1} ranging from **5.78 to 7.93** Mg TCM^{-1}

while it averaged **5.08 ± 0.39** Mg TCM^{-1} ranging from **4.28 to 5.81** Mg TCM^{-1} for manual harvesting system.

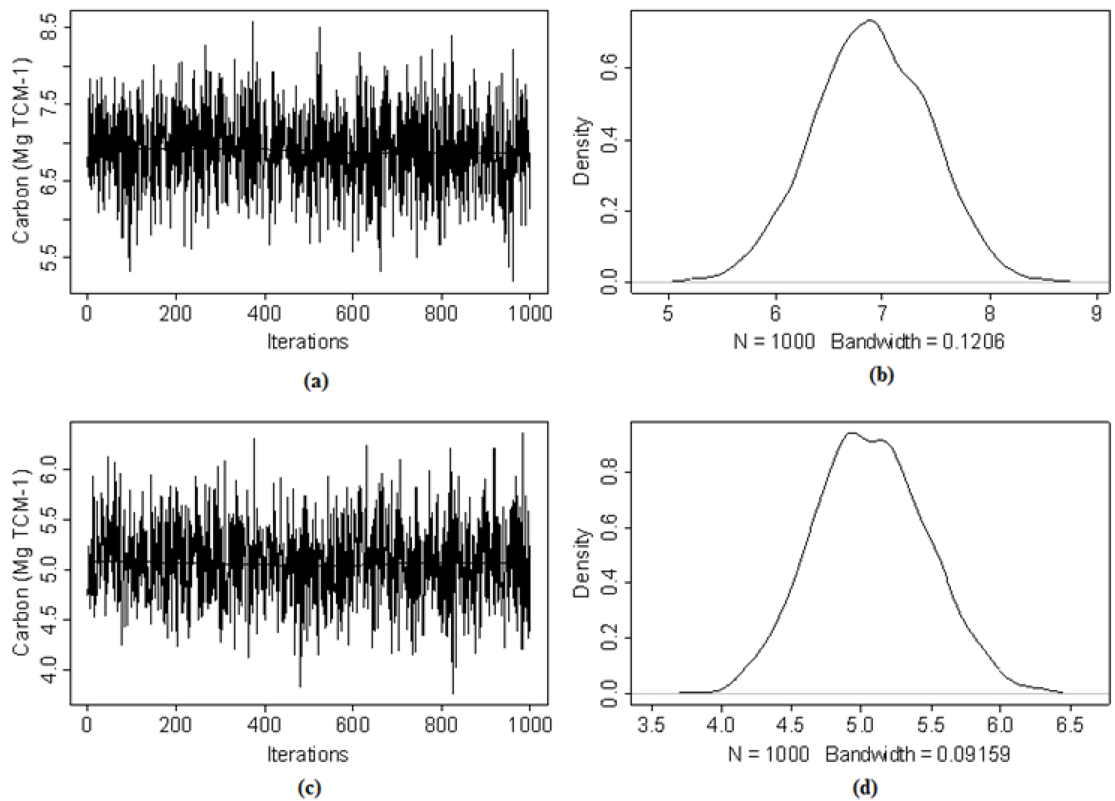
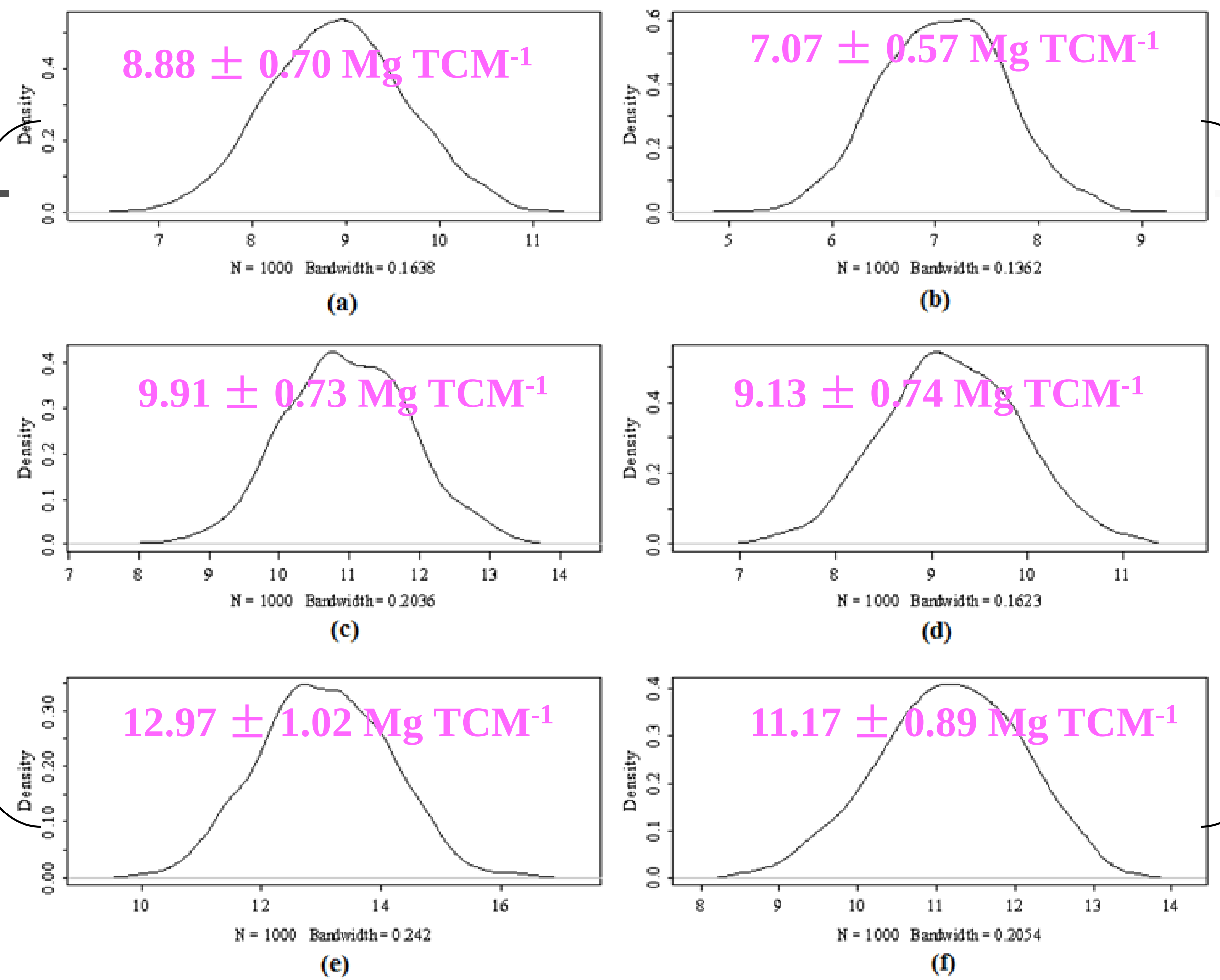


Figure 5. Trace plot and probability density plot of carbon emission (Mg TCM^{-1}) using mechanized (a) and (b) and manual (c) and (d) harvesting systems in the base case scenario of 80 km hauling distance.

mechanized harvesting systems



manual harvesting systems

Figure 6. Probability density of carbon emission (Mg TCM^{-1}) using mechanized (a, c, e) and manual harvesting systems (b, d, f) at three different hauling distances, i.e. 160 km (a, b), 240 km (c, d) and 320 km (e, f).

Conclusions

- Forest carbon removal due to harvesting, fire and limited dead trees does not significantly impair the existing forest carbon stock in West Virginia.
- An increase in the number of dead trees or harvesting intensity could reduce the net carbon balance of timberland.
- 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.

Conclusions (cont'd)

- 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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Thank You!

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