A Circular Forest and Biomass Energy Decarbonization System for Bioeconomy

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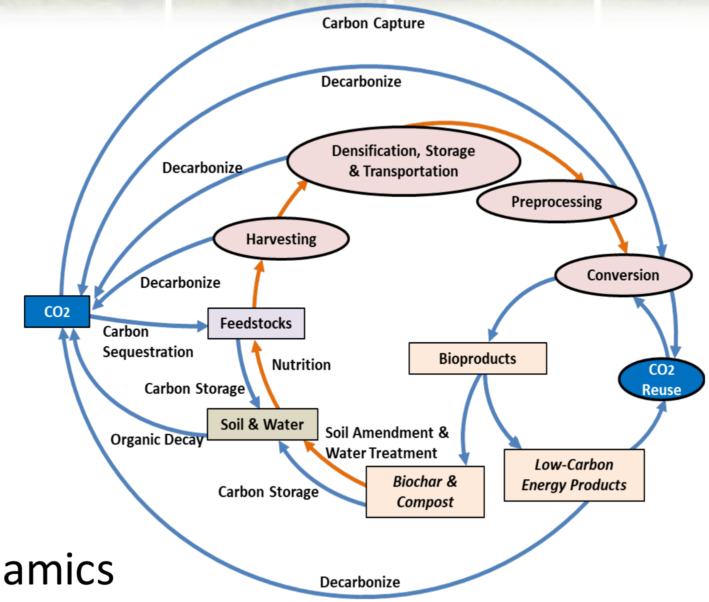
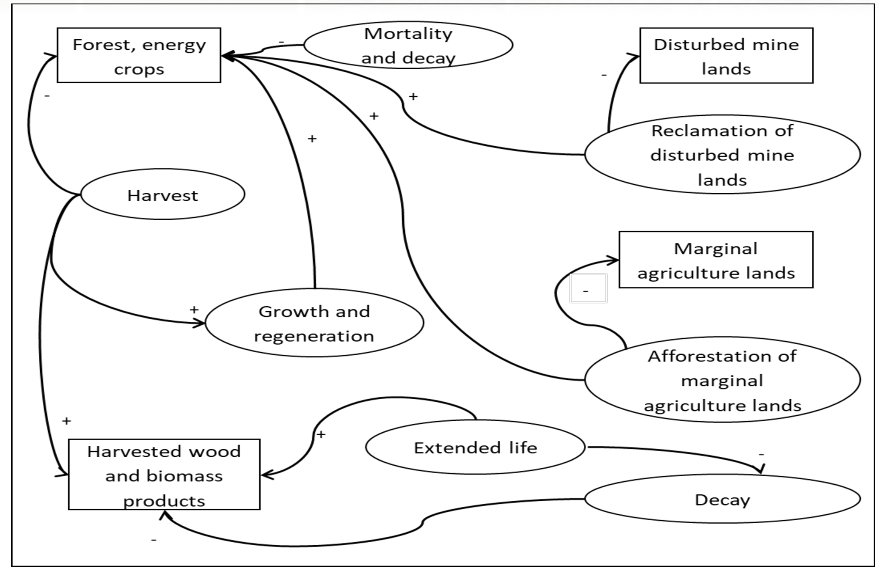
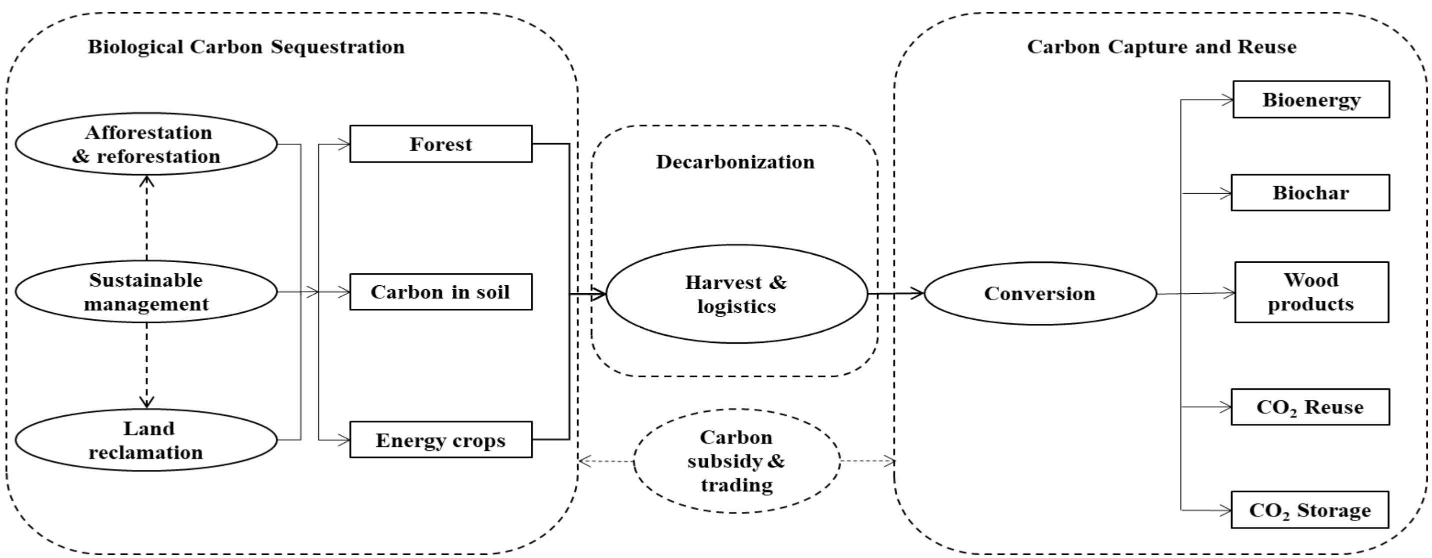
A Circular System for Decarbonization





System dynamics
Circular sustainable supply chains
Entity and actions
Pathways



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Decarbonization Option, Rate and Cost

Options	Practices	Carbon sequestration rate	Carbon sequestration cost	CO_2 utilization cost ($/t CO_2)
Afforestation & reforestation	Planting trees and bioenergy crops.	Average 1.50 t CO_2/ha/year, ranging from 1.19 to 4.59 t CO_2/ha/year for mixed hardwood forests[1]	$28-$83/tC [5] or $101-303/t$CO_2$	−40 to 10 [6]
Sustainable management	Sustainable harvest and scheduling.			
Land reclamation	Planting biomass crops in marginal lands.	50.6 to 94.8 t CO_2/ha for a 19-year period of shrub willow[2]		
Bioenergy with carbon capture & Storage (BECCS)	Utilizing forest and crop biomass to produce bioenergy substituting fossil fuel-based energy while CO_2 emitted during the process is captured and stored.	Global carbon sequestration potential 3.4 to 5.2 Gt CO_2/year[3]		60 to 160 [6]
Biochar	Pyrolyzing forest and crop biomass to produce biochar for soil amendment.	0.92 t CO_2 sequestrated by one ton of biomass[4]	$11-$167/tC [7] or $40-606/t$CO_2$	−70 to −60 [6]

*The unit carbon sequestration cost (CSC_t) at time t of a planning period T per unit area can be expressed as:

$$CSC_t = \frac{CC_t}{CS_t}, \quad t = 0, 1, 2, \ldots, T$$

where, CC_t is the net cost of the amount of CS_t carbon sequestered at t of a planning period T for a certain size of area or per unit area of forest or biomass crops.

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*CO_2 utilization cost is the cost in $/t CO_2 adjusted for revenues, by-products, and any CO_2 credits or fees. A cost of zero represents the point at which the pathway is economically viable without governmental CO_2 pricing (for example, a subsidy for CO2 utilization) [6].

1. Liu, W. 2015. West Virginia University; 2. Pacaldo, R. S., Volk, T. A., & Briggs, R. D. (2014). Bioenergy Research; 3. National Academies of Sciences, Engineering, and Medicine. (2018); 4. Yang, Q., Mašek, O., Zhao, L., Nan, H., Yu, S., Yin, J., & Cao, X. 2021. Applied Energy; 5. Stavins, R. N., & Richards, K. R. 2005; 6. Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., & Williams, C. K. 2019. Nature; 7. Richards, K. and C. Stokes. 2004. Climatic Change.

Forest Carbon Neutrality

A coefficient of carbon neutrality with consideration of carbon harvested, carbon growth, and life cycle emissions as:

$$CN_t = \frac{G_t + L_T - t\,L_T/Y_T}{H_0}$$

Where, $t = 0, 1, ..., T$, is the year after harvest.

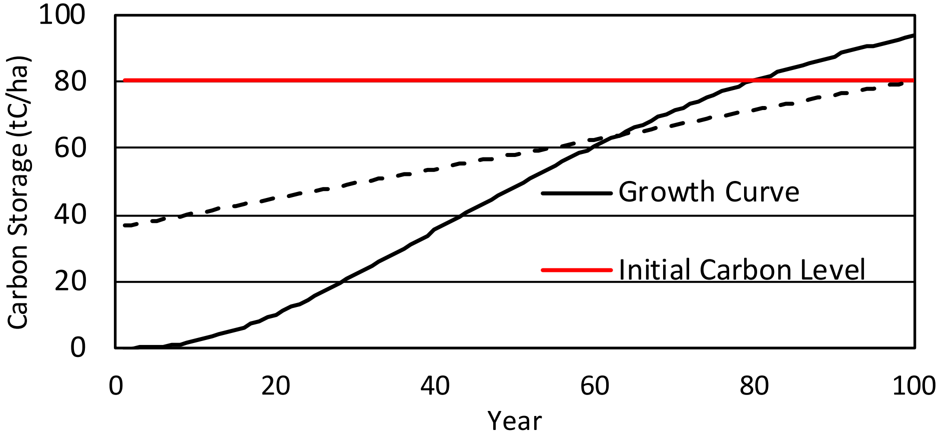
G_t is the accumulative carbon growth of forest stand at time t.

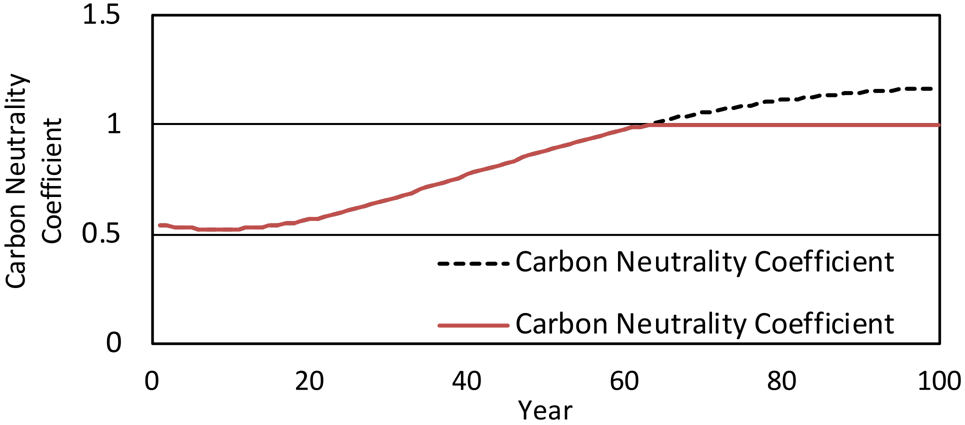
CN_t is the defined carbon neutrality coefficient over a life cycle of forest and harvested products.

L_T is the carbon of long-lived wood products.

H_0 is the total carbon harvested.

Y_T is the life span of long-lived wood product.





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Forest Carbon Accounting

In a forest ecosystem, carbon can be stored in the following **carbon pools** and can be estimated using a full carbon accounting approach:

$$TC_t = TL_t + BL_t + BD_t + SD_t + DDW_t + SH_t + FF_t$$

The objective of forest and biomass harvest scheduling process is to maximize the total revenue (z) of the forests and biomass in terms of carbon (C), timber (W), and biomass (B) values.

$$max \quad z = C + W + B$$

For example, *C* is the monetary value of carbon sequestered and is calculated by equation

$$C = r_{CO_2} p^{CO_2} \sum_{i=1}^{S} \sum_{t=1}^{T} \{ f_{ci}(a_{it}) - r_{dry} \delta x_{it} [G_{i,t-1} + f_{bi}(a_{i,t-1})] \}$$

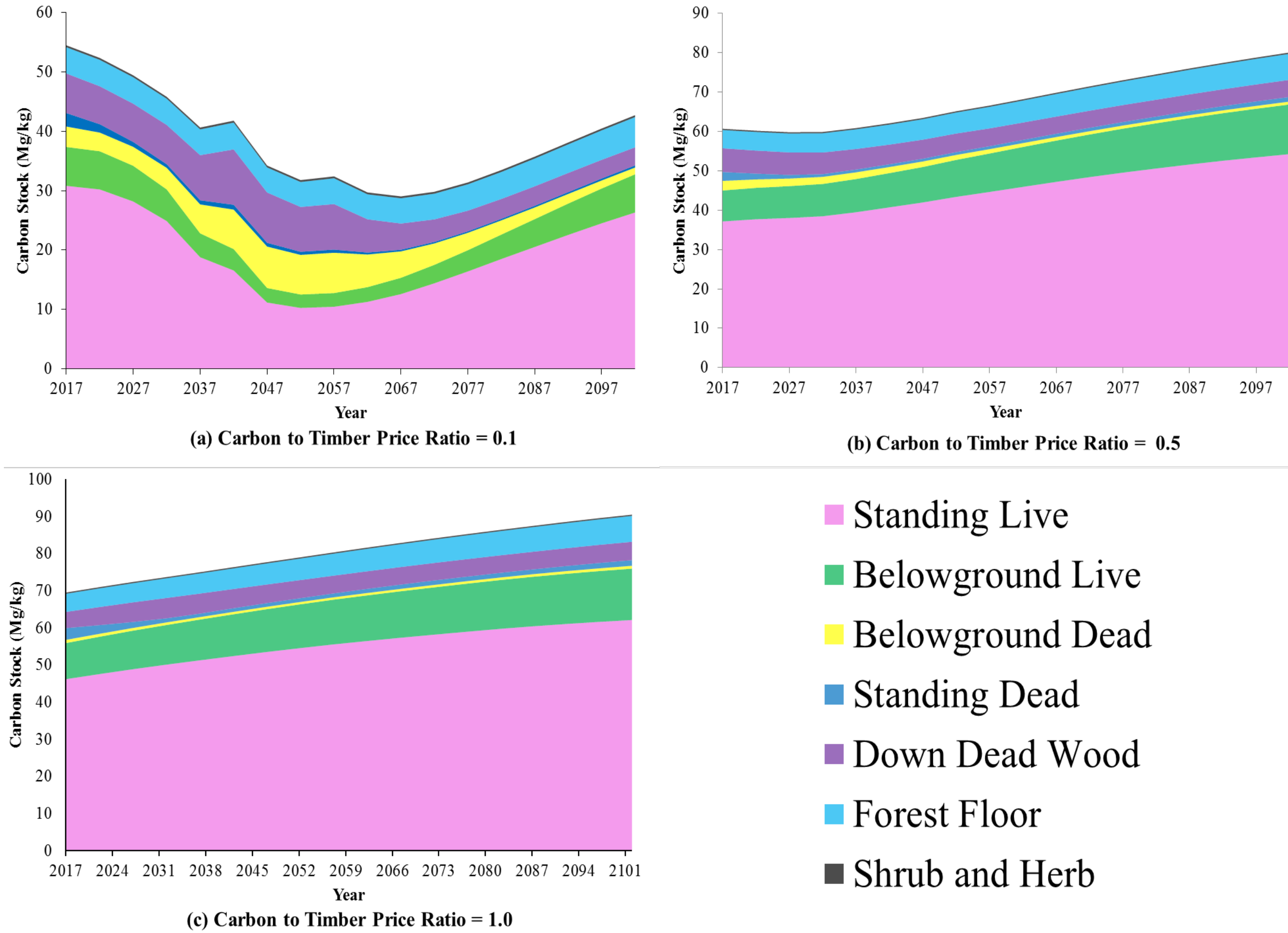
The management strategies should consider carbon and timber prices, biomass for energy, harvest area, harvest method, carbon storage, harvest rotation, subsidy and trading.

1. Sharma, B.D. 2010. Modeling of forest harvest scheduling and terrestrial carbon sequestration. Ph.D. Dissertation. West Virginia University Division of Forestry and Natural Resources. Morgantown, WV.
2. Liu, W. 2015. Economic and environmental analyses of biomass utilization for bioenergy products in the Northeastern United States. Ph.D. Dissertation. West Virginia University Division of Forestry and Natural Resources. Morgantown, WV.
3. Burkhart, H., T. Avery, and B. Bullock. 2019. Forest Managements (sixth edition). Waveland Press, Inc. Long Grove, IL.

Forest Carbon Management Strategies

For mixed Appalachian hardwood forests:

- The carbon sequestration rate of the base case scenario over the planning horizon of 50 years was $0.408\ \mathrm{Mg \cdot ha^{-1} \cdot year^{-1}}$.
- It ranges from 0.325 to $1.253\ \mathrm{Mg \cdot ha^{-1} \cdot year^{-1}}$ with an average of 0.917 $\mathrm{Mg \cdot ha^{-1} \cdot year^{-1}}$ as the carbon to timber price ratio increased from 0.0 to 1.0
- Among different carbon components, aboveground living stands were the major contributor (59.6%) to the total carbon storage, followed by belowground living component (15.6%).



(a) Carbon to Timber Price Ratio = 0.1

(b) Carbon to Timber Price Ratio = 0.5

(c) Carbon to Timber Price Ratio = 1.0

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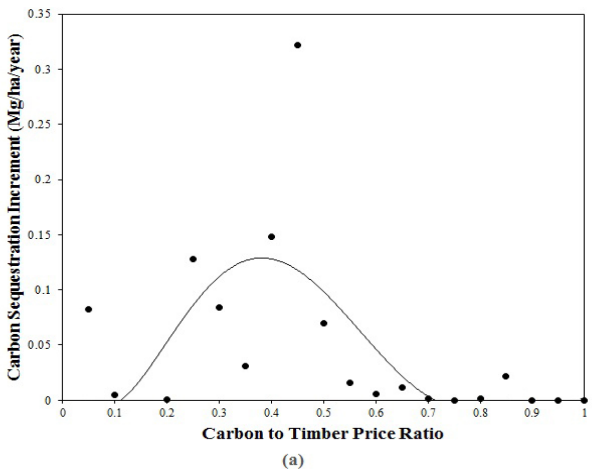
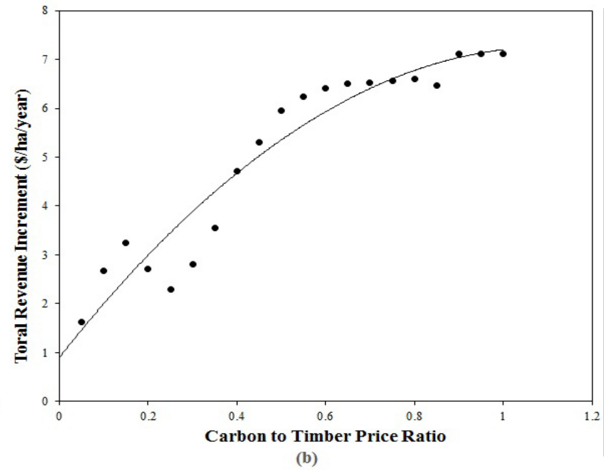
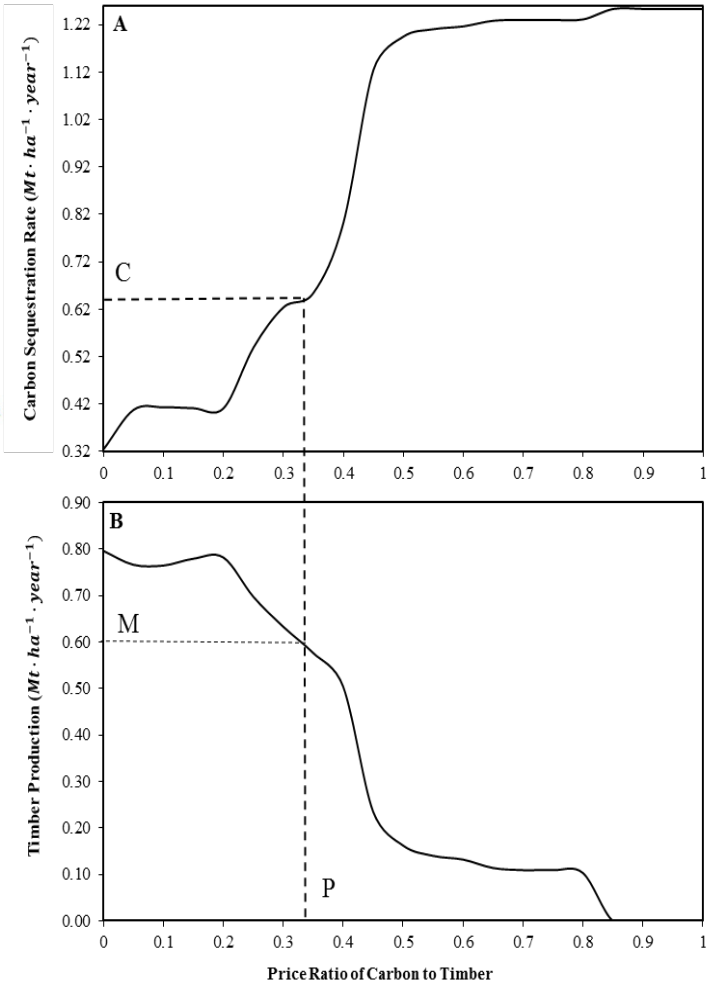
Forest Carbon Management Strategies

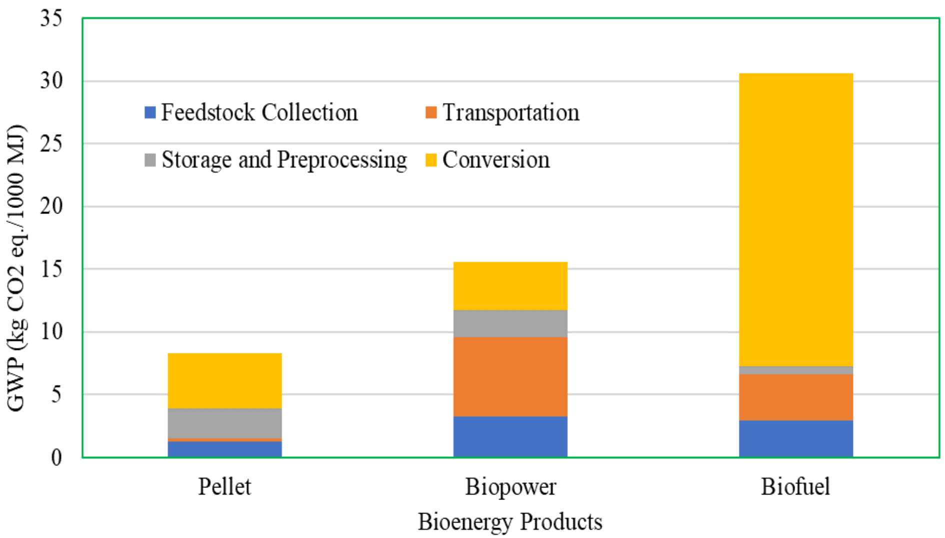


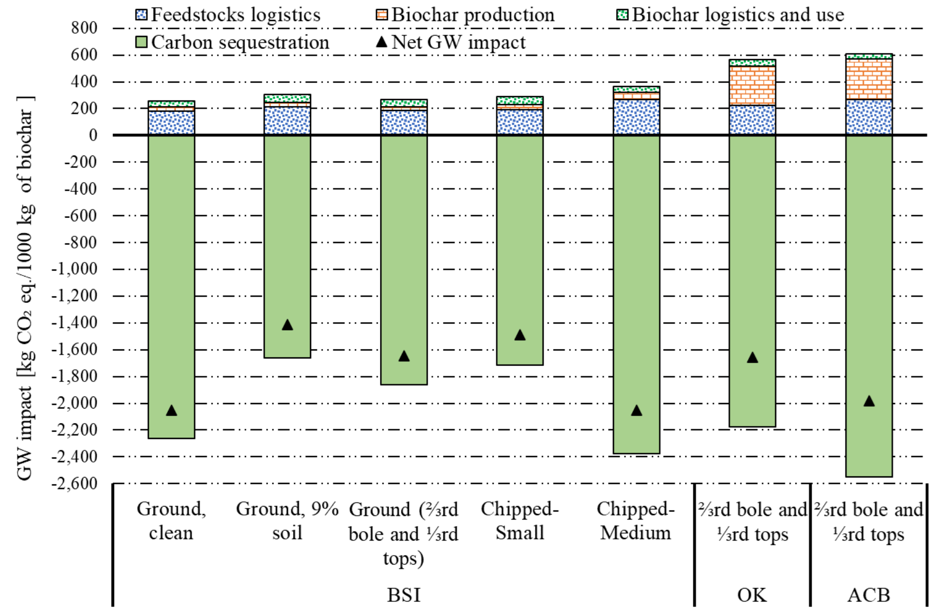




- Marginal rate is identified when the carbon to timber price ratio is at 0.45.
- The revenue steadily increases from \$1.6 to \$7.1 $ha^{-1} \cdot year^{-1}$.
- When the price ratio is greater than or equal to 0.8, the increment of forest revenue reached to a flat plateau.
- The carbon to timber price ratio is a tradeoff between carbon stock and timber demand.
- To achieve a carbon sequestration rate of C (0.64) tons/ha/yr, a carbon to timber price ratio should be P (0.33), then M (0.6) $\mathrm{Mg} \cdot \mathrm{ha}^{-1} \cdot \mathrm{year}^{-1}$ for a potential management practice.

Forest Carbon Management Strategies





Life cycle GWP of bioenergy products:

Pellet production presented the lowest GHG emissions and consumed the least amount of fresh water and fossil fuels. Pyrolysis oil production emitted the highest amount of greenhouse gas, which was double of biopower production.

The results illustrated that the global warming potential (GWP) impact of biochar production through BSI, OK, and ACB were 0.25–0.39, 0.55, and 0.61 tonne CO_2eq./tonne biochar applied to the field

1. Wang, Y., J. Wang, X. Zhang, and S. Grushecky. 2020. Environmental and Economic Assessments and Uncertainties of Multiple Lignocellulosic Biomass Utilization for Bioenergy Products: Case Studies. Energies 2020, 13, 6277.
2. Sahoo K. et al. 2021. Life-cycle assessment and techno-economic analysis of biochar produced from forest residues using portable systems. The International Journal of Life Cycle Assessment. 26(1): 189-213.

Thank You!

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