The Effect of Forest Growth Rate on Climate Change Impacts of Logging Residue Utilization

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The total CCI of bioenergy (E_T, kg CO_2 eq) is consisted of four components: fossil fuel-derived GHG emissions (E_{fossil}, kg CO_2 eq), biogenic GHG emissions (E_{bio}, kg CO_2 eq), biomass regrowth for compensation (E_{com}, kg CO_2 eq) and the difference in carbon sequestration (E_{diff}, kg CO_2 eq) (Eq. S1).

$$E_T = E_{fossil} + E_{bio} + E_{com} + E_{diff}$$

$$= E_{fossil} + \frac{44}{12}\delta[E(0)GWP_{bio} + COM + C_C] \qquad (S1)$$

(1) Fossil fuel-derived GHG emissions (E_{fossil})

This component comes from the CCI of GHG emissions from burning fossil fuels. Fossil fuel-derived GHG emissions for the production of bioethanol and biodiesel are all derived from the GREET database [1].

In the LCA framework, we used the data from the GREET database. To illustrate the uncertainty in LCA, we introduced a range of greenhouse gas emissions from fossil fuels (Table S1). The range varies according to different future climate scenarios (2°C, 4°C, and 6°C) and LCA emissions factors (max, min, and average). The 2°C Scenario (2DS) offers a vision of a sustainable energy system of reduced greenhouse gas and carbon dioxide (CO2) emissions; the 4°C Scenario (4DS) reflects stated intentions by countries to cut emissions and boost energy efficiency; the 6°C Scenario (6DS), is where the world is now heading with potentially devastating results (International Energy Agency, IEA, 2014). The maximum and minimum LCA emissions factors for light- and middle- & heavy-distillate fuels are defined by the values for gasoline and diesel derived from Canadian oil sands and conventional crude production [2]

Table S1. Triangular distribution parameters for light- and middle- & heavy-distillate transportation fuel final energy.

	Light distillate fuel kg CO_2 eq/GJ			Middle & heavy distillate fuel kg CO_2 eq/GJ		
Scenarios	Min	Max	Average	Min	Max	Average
2DS			97.6			91.2
4DS	95.2	117	98.7	88.9	109.9	92.3
6DS			99.0			92.6

(2) Biogenic GHG emissions (E_{bio})

Biogenic CO_2 emissions are the CCI of CO_2 emissions from biomass that is retained in the atmosphere. The initial biomass GHG emissions are multiplied by the global warming potential to obtain the biogenic GHG emissions (Eq. S2).

$$E_{bio} = \frac{44}{12}\delta E(0)GWP_{bio} \qquad (S2)$$

δ is the area of land required to support 1 GJ energy equivalent biofuel production (Eq. S3). $\frac{44}{12}$ is the conversion factor of carbon to CO_2. $E(0)$ is the initially available forest biomass after collecting logging residues. GWP_{bio} is the global warming potential of CO_2 from bioenergy (Eq. S4).

$$\delta = \frac{1}{\rho E(0)} \tag{S3}$$

ρ is energy conversion efficiency, which is obtained from GREET 2021 database: bioethanol: 0.0174 GJ/kg C logging residues; bio-diesel: 0.019 GJ/kg C logging residues.

$$GWP_{bio} = \frac{AGWP_{bio}}{AGWP_{co_2}} \tag{S4}$$

$AGWP_{bio}$ is the actual absolute global warming potential of biogenic CO_2 emissions (Eq. S5). $AGWP_{co_2}$ is the absolute global warming potential of carbon emissions (Eq. S6).

$$AGWP_{CO_2}(T) = \int_0^T \alpha_{CO_2} y(t) E(0) dt \tag{S5}$$

$$AGWP_{bio}(T) = \int_0^T \alpha_{CO_2} E(t) dt \tag{S6}$$

T is the time horizon for the CCI and in this study $T = 100$. α_{CO_2} is the radiative forcing of atmospheric CO_2. $y(t)$ is remained CO_2 in the atmosphere after years t of fossil energy CO_2 emissions (Eq. S7). It can simulate the decay of CO_2 in the atmosphere, which is derived from the Bern2.5CC carbon cycle mode [3]. $E(t)$ is is the biogenic CO_2 emissions that remained in the atmosphere in year t (Eq. S8).

$$y(t) = y(0) + \sum_{i=1}^{3} y_i e^{-\frac{t}{\tau_i}} \tag{S7}$$

y_i and τ_i are parameters. $y_0 = 0.217$, $y_1 = 0.224$, $y_2 = 0.282$, $y_3 = 0.276$, $\tau_1 = 394.4$, $\tau_2 = 36.54$, $\tau_3 = 4.304$.

$$E(t) = \frac{y(t)[E(t-1) - B(t-1)]}{y(t-1)} \tag{S8}$$

For $E(t) < 0$, set $E(t) = 0$. And $B(0)$ equals 0. $B(t)$ is the forest biomass in year t (Eq. S9).

$$B(t) = A(t) - A(t-1) \tag{S9}$$

$A(t)$ (kg C/ha, t is year t) is the cumulative forest biomass.

(3) Biomass regrowth for compensation (E_{com})

$$E_{com} = \frac{44}{12} \delta COM \tag{S10}$$

COM is part of the biomass-derived GHG compensated by biomass regrowth.

$$COM = \int_1^T GWP(t) COM(t) dt \tag{S11}$$

$GWP(t)$ is the global warming potential of CO_2 emissions in year t (Eq. S12). The $COM(t)$ for COM in year t (Eq. S13).

$$GWP(t) = \frac{\int_t^T y(t'-t) dt'}{\int_0^T y(t) dt} \tag{S12}$$

$$COM(t) = \begin{cases} B(t), & E(t) > B(t) \\ E(t), & E(t) \le B(t) \end{cases} \tag{S13}$$

(4) The difference in carbon sequestration (E_{diff})

Carbon sequestration is different between logging residue utilization scenario and the reference scenario. Therefore, the difference should be considered in CCI and is named as the difference in carbon sequestration (Eq. S14).

$$E_{diff} = \frac{44}{12}\delta C_C \tag{S14}$$

C_C is calculated as the sum of $GWP(t)$ and the carbon sequestration in year t within 100 years (Eq. S15).

$$Cc = \int_1^T GWP(t)[D'(t) - D(t)]dt \tag{S15}$$

$D(t)$, $D'(t)$ are the CO_2 emissions (kg CO_2 eq/ha) for logging residues utilization and reference scenarios in year t.

$$D(1) = S(1) + R - S(0) \tag{S16}$$

$$D(t) = S(t) - S(t-1), t \geq 1 \tag{S17}$$

$$D'(t) = S'(t) - S'(t-1), t \geq 1 \tag{S18}$$

$$S(0) = S'(0) \tag{S19}$$

$S(t)$, $S'(t)$ are the carbon stocks (kg C/ha) for logging residues utilized versus not utilized in year t. When the logging residues don't be used, the decomposition of logging residues can be simulated by YASSO15. It is worth noting that the scenarios of using logging residues also have naturally decomposed parts. R is initially available logging residues, which equals $E(0)$.

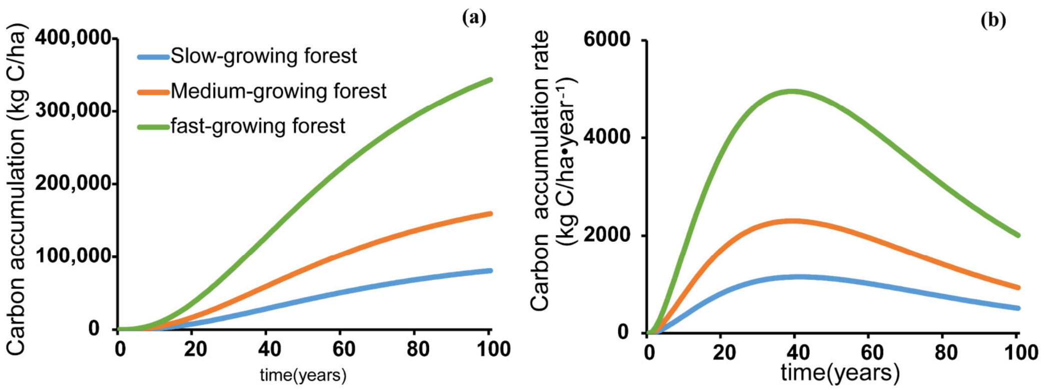

Figure S1. The forest regrowth with different growth rates was simulated by the Chapman-Richards function, a) the forest carbon accumulation; b) the forest carbon sequestration rates.

Table S2. A notation list for the framework.

Notation	Definition
LCA	Life cycle assessment
GHG	Greenhouse gas
CCI	Climate change impacts
$B(t)$	The annual biomass regrowth
E_T	The total climate change impacts of bioenergy
E_{fossil}	The fossil fuel-derived GHG emissions
E_{bio}	The biogenic GHG emissions
E_{com}	The biomass regrowth for compensation

E_{diff}	The difference in carbon sequestration between the biomass utilization scenarios and the reference scenario
$E(0)$	The initial pulse of CO_2
$E(t)$	The remaining biomass-derived CO_2 emissions in the atmosphere at time t
$AGWP_{bio}(T)$	The absolute global warming potential of a biomass-derived CO_2 pulse
$AGWP_{CO_2}(T)$	The absolute global warming potential of a fossil fuel-derived CO_2 pulse
GWP	Global warming potential
GWP_{bio}	Global warming potential of biomass-derived CO_2 emissions
COM	The Regrowth for compensation
$COM(t)$	The biomass regrowth accounted for as compensation for CO_2 emissions in year t
C_C	The difference in carbon sequestration
$D(t)$	The carbon sequestration in year t with biomass utilization
$D'(t)$	The carbon sequestration in year t with no biomass utilization
$S(0)$	The final carbon storage in the year of biomass utilization
$S(t)$	The carbon storage in year t with biomass utilization
$S'(0)$	The final carbon storage if the biomass is not utilization
$S'(t)$	The carbon storage in year t with no biomass utilization
T	The time horizon
t	Time (year) after biomass utilization or CO_2 emission
δ	The area of land required to support 1 GJ energy equivalent biofuel production (ha)
ρ	Energy conversion efficiency

References

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