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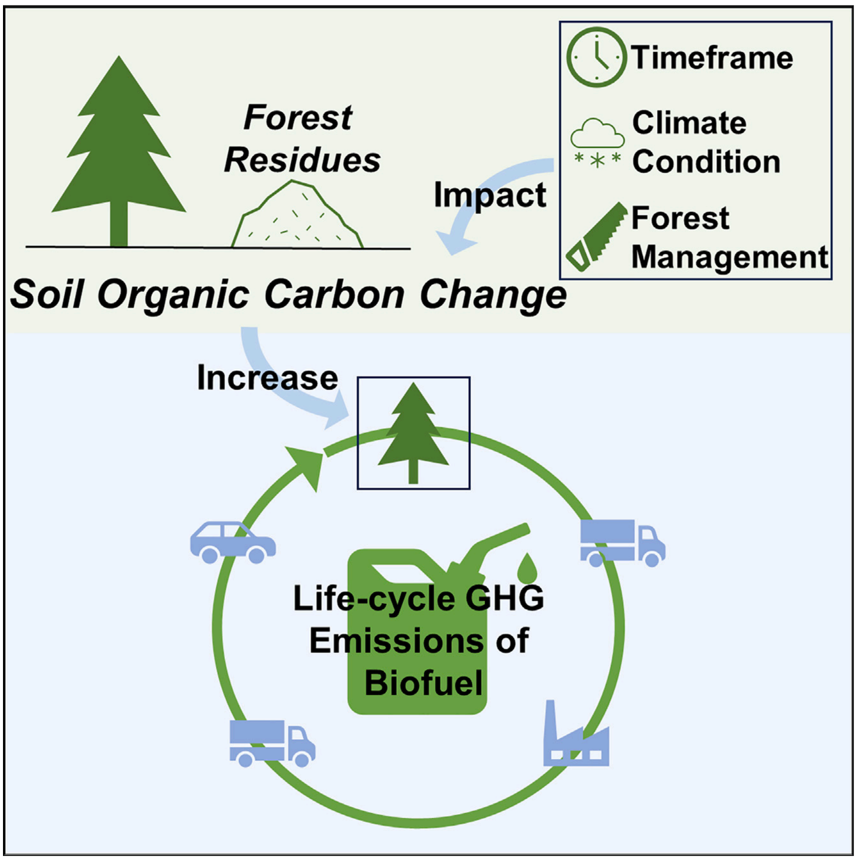
Soil organic carbon change can reduce the climate benefits of biofuel produced from forest residues



We investigate the impact of soil organic carbon changes on the carbon intensity of forest residue-derived biofuels. This impact is often overlooked in life cycle assessments (LCAs) adopted by regulatory agencies. We find that removing forest residues adds 8.8–14.9 $gCO_2e\ MJ^{-1}$ of greenhouse gas (GHG) emissions, accounting for 20.3%–65.9% of biofuel carbon intensity. This impact varies by time frame and climate conditions. Our findings highlight the importance of considering soil carbon assessment in future LCAs, policymaking, and forest management.

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Highlights

SOC change due to forest residue removal contributes to significant GHG emissions

SOC-associated GHG emissions have significant impacts on the biofuel carbon intensity

The impacts of SOC change vary by time frame and climate conditions

Life cycle assessment of residue biofuels needs to include soil carbon assessment

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Soil organic carbon change can reduce the climate benefits of biofuel produced from forest residues

Kai Lan,[1,2] Bingquan Zhang,[1,2] Tessa Lee,[1] and Yuan Yao[1,3,*]

SUMMARY

Because biomass residues do not cause land-use change, soil carbon changes are commonly not considered in life cycle assessments (LCAs) of biofuel derived from forest residues adopted by regulatory agencies. Here, we investigate the impacts of soil organic carbon (SOC) changes caused by removing forest residues in the Southern US on the carbon intensity of biofuels. We show that the average greenhouse gas (GHG) emissions by SOC changes over 100 years are 8.8–14.9 gCO_2e MJ^{-1}, accounting for 20.3%–65.9% of life cycle GHG emissions of biofuel. These SOC-associated GHG emissions vary by time frame, site conditions, and forest management strategies. For land management, converting forest residues to biofuel is more climate beneficial than on-land decay or pile burning, depending on fossil fuel substitution and site conditions. Our results highlight the need to include soil carbon assessment in biofuel LCAs, policymaking, and forest management, even when forest residues are used and no land-use change is involved.

CONTEXT & SCALE

Replacing fossil fuels with biofuels offers a promising path to decarbonizing the transportation sector, a major source of greenhouse gas emissions (GHGs). Utilizing waste biomass such as forest residues is particularly appealing, as it avoids land-use change and associated GHG emissions. Current biofuel life cycle assessment (LCA) adopted by regulatory agencies considers forest residues as carbon-neutral feedstock and typically ignores soil organic carbon (SOC) changes from residue removal. Our study quantifies SOC change caused by removing forest residues in the Southern US and found that they can make a substantial contribution to the carbon footprint of biofuel derived from forest residues. Our results emphasize the need to include soil carbon assessment in future LCAs, biofuel policy, and forest management, even when waste biomass is used and no land-use change is involved.

INTRODUCTION

Converting renewable biomass to biofuel has great potential to enhance energy security and reduce the environmental impacts of the transportation sector,[1–3] which accounts for 27% of the total US greenhouse gas (GHG) emissions (5,981 $MtCO_2e$) in 2020.[4] Among various biomass feedstocks, the critical role of biomass residues in supporting bioenergy supply has been highlighted in future climate change mitigation scenarios.[5,6] In the US, forest residue is one of the most abundant biomass feedstocks, which are generated in thinning, logging, and wood product manufacturing.[7] These forest residues are currently underutilized because they are either left on-site or, much less commonly, burned for energy recovery. Converting forest residues to biofuels can enhance forest resource utilization, reduce the risks of forest wildfire, and bring additional revenue to landowners.[8–10] In the Southeastern US, forest residues, along with sawmill residues and low-value trees, are manufactured into over 4 million Mg of wood pellets.[11]

Many studies have highlighted the value of biomass residues in avoiding land-use change and relevant carbon emissions, in contrast to dedicated biomass, such as corn.[12,13] Therefore, changes in soil carbon stock are often ignored for biomass residues, such as forest residues, in previous life cycle assessment (LCA)[14–18] and low-carbon fuel policies, such as the Renewable Fuel Standard (RFS) by the US Environmental Protection Agency (EPA) that qualifies forest residues and precommercial thinning from non-federal forestland as renewable biomass for bioenergy.[19] However, forest residues play an essential role in the forest carbon cycle[20] and provide ecosystem services, such as preventing erosion and maintaining forest productivity and diversity.[21,22] Previous studies show that intensive forest residue removal may lead to long-term soil organic carbon (SOC) loss,[20,23–26] affecting the carbon intensity of biofuels. Other studies on agriculture residues also showed SOC loss due to agriculture residue removal for biofuel production.[27,28] The ignorance of SOC changes may result in overestimating the climate benefits of forest residue-derived biofuels. The quantity and impacts of SOC change highly depend on forest management practices,[29–31] counterfactual scenarios (e.g., forest residues left on-site or burned), and the composition of forest residues, all of which have not been investigated in the previous LCA for forest-residue-derived biofuels. Understanding the impacts and driving factors of SOC changes associated with forest residual removal and utilization is essential to the simultaneous development of sustainable forest management and low-carbon biofuels.

Here, we established a dynamic life cycle modeling framework to investigate the impacts of SOC changes due to forest residue removal on the life cycle carbon footprint of biofuels derived from forest residues. The framework was applied to a cradle-to-grave biofuel system using fast pyrolysis to convert pine residues in the Southern US to hydrocarbon biofuels (diesel- and gasoline-range products). This framework integrates a forest growth model, SOC model, biorefinery process model, and Monte Carlo simulation (MCS). The model was run on a year-by-year basis to provide a holistic understanding of dynamic inventory data (e.g., carbon flows) across natural (forest and soil) and industrial systems (biorefinery and biomass logistics). Scenarios were established to study the impacts of SOC changes related to the variations in forest growth and management, climate conditions, and counterfactual scenarios. This study presents a parametric approach that quantitatively links the critical parameters related to biomass quality (e.g., moisture, carbon, and ash content), forest dynamics (e.g., operations, growth, and management strategies), and SOC dynamics with the LCA model through process simulations. This approach can be applied to other bioenergy systems with different biomass residue feedstocks and conversion technologies to enable a better understanding of the impacts of biomass residue removal and utilization. Such understanding is critical for the planning and optimization of future bioenergy systems.

RESULTS

Methods summary

As shown in Figure 1, this study includes nine scenarios (S1–S9), including three representative forest growth cases (GC1–GC3) combined with two historical climate condition cases varied by geospatial locations and two extreme climate change conditions in 2050 and 2100 specific for SOC modeling with static climate data, along with one scenario with carbon capture and storage (CCS). Both forest growth and SOC modeling used static historical climate data as inputs. To evaluate the model sensitivity to climate change, we did an additional test using static future climatic conditions, but only in SOC modeling. The loblolly pine was selected as one of the most commonly planted species in the Southern US (planted on over 13.9 million hectares [ha]).[32] Three growth cases represent varied site productivities and common forest management practices in the Southern US, whereas two climate conditions (i.e., varied annual average temperature and precipitation) were adopted to show their impacts on SOC change (e.g., varied decay rates of SOC pools) and further on the system-wide carbon intensity (see section methodology). Details of conceptually defined carbon pools in the SOC model are documented in Note S1. In each scenario, three residue end-of-life cases were modeled to understand the implications of varied residue management methods. In the baseline case, all forest

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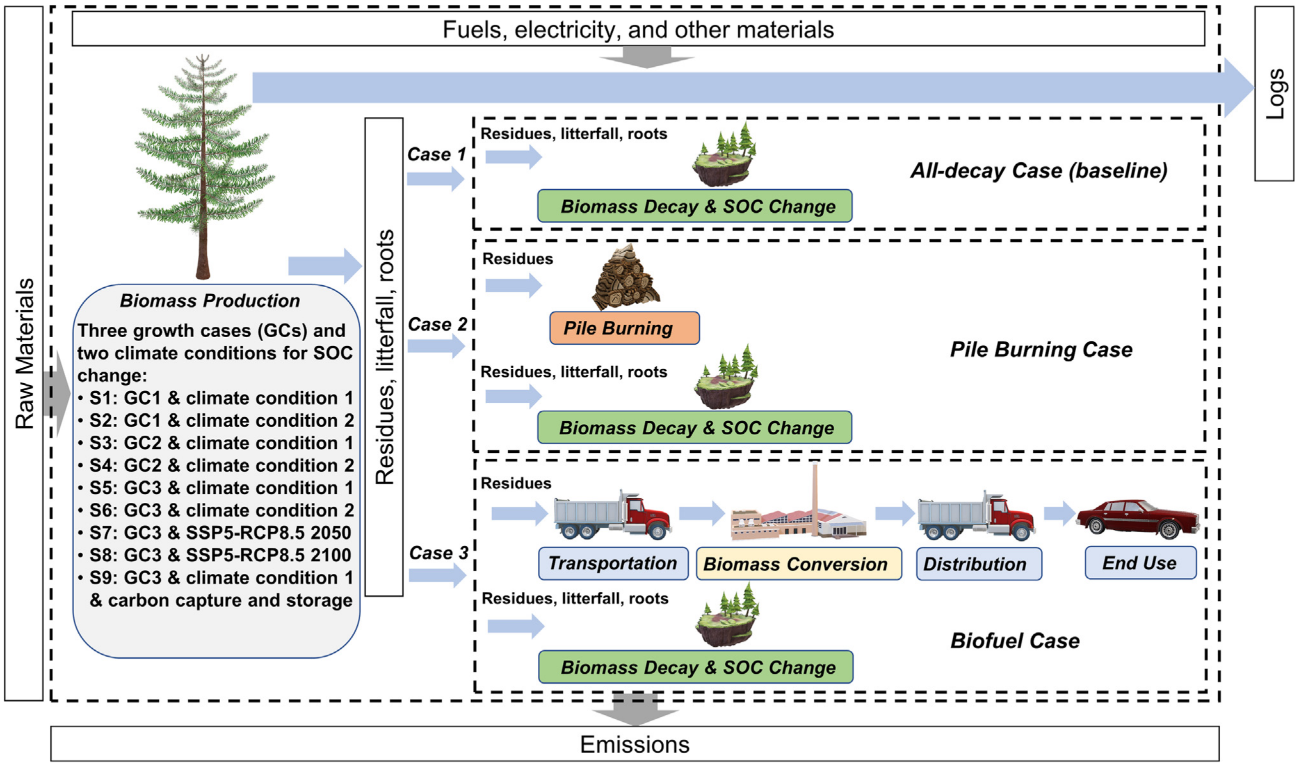

Figure 1. The system boundaries of three varied end-of-life cases of forest residues

The system contains the combination of three forest growth cases (GCs) and four climate conditions for forest SOC change. In the all-decay case, all the residues are left on-site for decay. In the pile burning case, a portion of the residues is piled and burned as part of the site preparation process prior to replanting. In the biofuel case, a portion of the residues is collected to produce biofuel via fast pyrolysis. The system boundary is cradle-to-grave: case 1 includes raw material extraction, biomass production, and biomass decay and SOC change; case 2 includes raw material extraction, biomass production, biomass decay and SOC change, and biomass pile burning; case 3 includes raw material extraction, biomass production, biomass decay and SOC change, transportation, biofuel production and distribution, and biofuel and co-product end use.

residues are left on the forest land for natural decay. The biofuel case collects a portion of the forest residues (50% in this study) for biofuel production.[7,33–36] Pile burning, a method for treating forest residues and preparing forest sites, collects and burns forest residues.[37–40] To examine the effect of future biorefinery decarbonization, this study includes a CCS case in scenario 9. The cradle-to-grave system boundaries include all activities presented in Figure 1 and the upstream production and transportation of fuels, electricity, and chemicals used in scenarios. GHG emissions accounted in this study include CO_2, CH_4, and N_2O. Detailed settings of scenario analysis are available in section methodology and Table S1.

Forest growth and yield

The quantity of forest residues depends on forest growth and yields modeled in three growth cases (GC1–GC3) on 1 ha (10,000 m^2) for 1 rotation, as shown in Figure 2. The forest in this study is sequentially reforested with a 25-year rotation, a typical rotation length for loblolly pine management.[41] GC1 represents low site productivity without precommercial thinning. GC2 has a high site productivity without precommercial thinning. In GC3, the forest with high site productivity has precommercial thinning in year 12. Thinning or logging residues are treated (i.e., collected, left on-land, or pile burnt) after thinning (year 12 in GC3) or logging (year 25). This study also considers the negative impact of removing residues (in biofuel and pile burning cases) on tree growth.[42] More details are in section methodology.

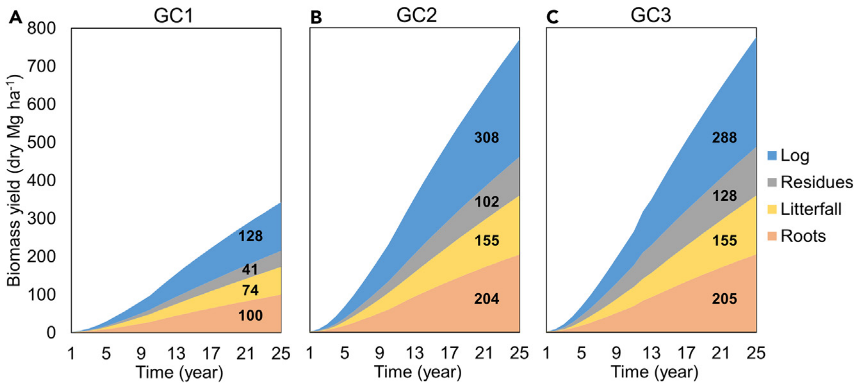

Figure 2. Forest growth and yield of three growth cases on 1-ha forest land for 1 rotation without removing forest residues in the all-decay case

(A) GC1 stands for low site productivity without precommercial thinning.

(B) GC2 represents high site productivity without precommercial thinning.

(C) GC3 has high site productivity with precommercial thinning in year 12. The figure shows the accumulative biomass yield (in dry Mg per ha) for 1 rotation (25 years) in three growth cases (GC1–GC3). The number in each area shows the accumulative yield value in year 25.

Among the three growth cases, GC3 in Figure 2C has the highest residue output (128 dry Mg ha^{-1}) due to the precommercial thinning that generates 38.3 dry Mg of residues (see Table S2 and section methodology). GC2 in Figure 2B has the highest log output (308 dry Mg ha^{-1}). GC1 has the lowest yields for both logs and residues due to low site productivity. From the biofuel perspective, GC3 is the best, given the highest residue output. From the log perspective, GC2 is preferable due to the highest log yield. Balancing the trade-off between log and residue production is complex and largely depends on local economic factors and landowners' choices.[43] Because this study focuses on forest residue to biofuel, logs are excluded from the system boundary (see Figure 1), and their carbon flows of further usage have been studied in the literature.[41,44,45]

GHG emissions of 1-MJ biofuel

Figure 3A displays the life cycle GHG emissions of biofuels compared with the baseline gasoline (93.1 gCO_2e MJ^{-1}) and qualified renewable gasoline (37.2 gCO_2e MJ^{-1}, 60% GHG reduction) in the US EPA RFS program.[46] The life cycle GHG emissions of RFS baseline diesel (91.9 gCO_2e MJ^{-1}) and qualified renewable diesel (36.8 gCO_2e MJ^{-1}, 60% GHG reduction) are very close to gasoline.[46] Because biochar is one of the products of fast pyrolysis (the others are bio-oil and non-condensable gases [NCGs]), biochar end-uses directly affect the life cycle GHG emissions of biofuels.[43] In the energy beneficial case, biochar is burned to generate power. Alternatively, biochar can be applied as a soil amendment that provides a stable carbon sink in the carbon beneficial case (see section methodology for more details).[47] Figure 3B shows the life cycle GHG emissions in varied time frames for scenario 5. The breakdown results of Figure 3A are shown in Figure 3C, and the source numbers are available in Data S1 (see data and code availability).

Figure 3A shows that removing forest residues for biofuel production causes SOC loss in the forest land across 100 years, which is consistent with the literature[23] and substantially increases the total life cycle GHG emissions of biofuels. Specifically, for a biorefinery without CCS (scenario 1–scenario 8), the mean GHG emissions from SOC change are 8.8–14.9 gCO_2e MJ^{-1}, which are 20.3%–34.6% of the life cycle GHG emissions (43.1 gCO_2e MJ^{-1}) in the energy beneficial case and increase to 34.3%–65.9% in the carbon

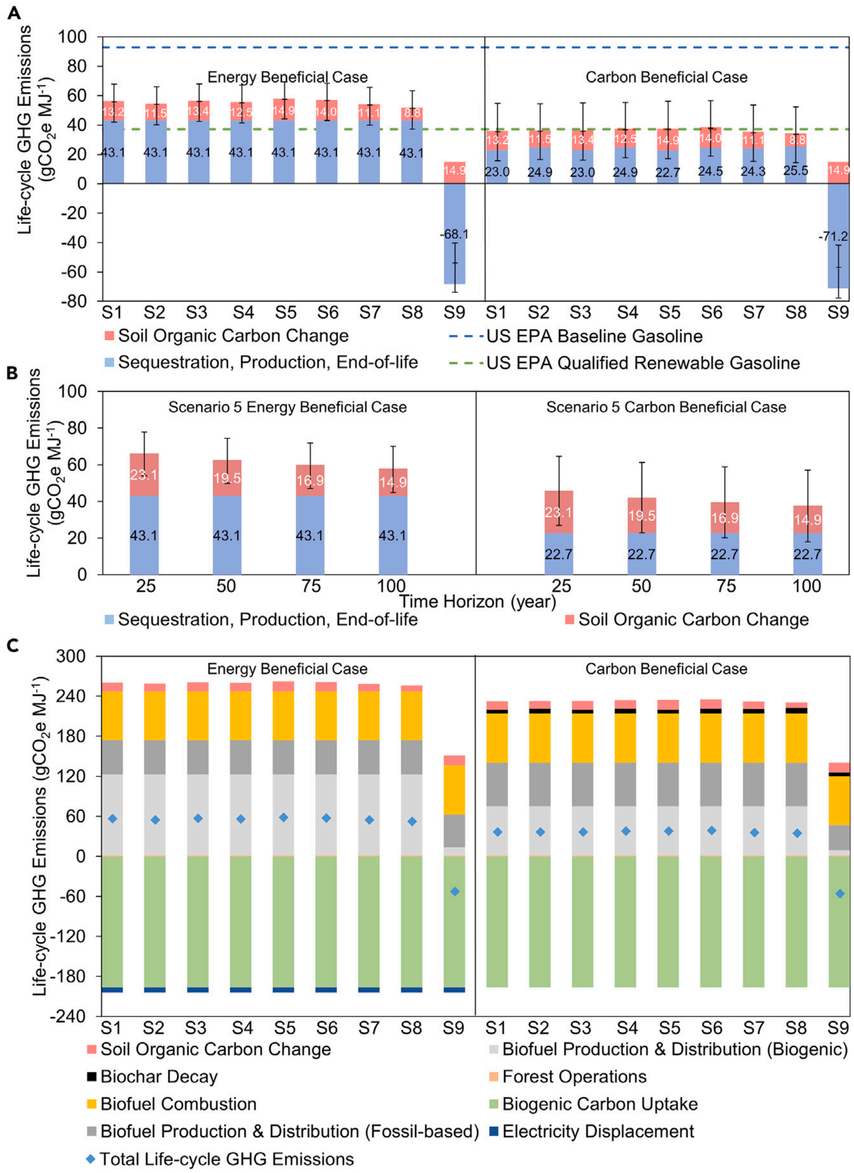

Figure 3. Total life cycle GHG emissions of 1-MJ biofuel

(A) GHG emissions of 1-MJ compared with US EPA baseline gasoline and qualified renewable gasoline with a 100-year time frame for soil organic carbon change.

(B) GHG emissions of 1-MJ biofuel with various time frames for soil organic carbon change in scenario 5.

(C) Average result breakdown of (A). The energy beneficial case combusts the biochar to generate power, whereas the carbon beneficial case applies the biochar as a soil amendment. The GHG emission of soil organic carbon change is for the 100-year time frame. The summation of bars in (C) (net values marked by diamonds) is equal to the summation of the average values in (A). S1: low site productivity and lower annual temperature and precipitation; S2: low site productivity and higher annual temperature and precipitation; S3: high site productivity and lower annual temperature and precipitation; S4: high site productivity and higher annual temperature and precipitation; S5: high site productivity with precommercial thinning and lower annual temperature and precipitation; S6: high site productivity with precommercial thinning and higher annual temperature and precipitation; S7: S5 with climate change condition of 2050; S8: S5 with climate change condition of 2100; S9: S5 with carbon capture and storage technology. Error bars represent the P5–P95 range of MCS.

beneficial case (22.7–25.5 $gCO_2e\ MJ^{-1}$). For total life cycle GHG emissions (including SOC change), SOC change accounts for 16.9%–25.7% in the energy beneficial case and 25.5%–39.7% in the carbon beneficial case. In scenario 9, the mean GHG emissions from SOC changes are 14.9 $gCO_2e\ MJ^{-1}$, which is a primary carbon emission source because CCS makes the biorefinery net carbon negative (life cycle GHG emissions −68.1 $gCO_2e\ MJ^{-1}$ in the energy beneficial case and −71.2 $gCO_2e\ MJ^{-1}$ in the carbon beneficial case). Hence, the emissions from SOC change should be included in the LCA of biofuels derived from forest residues, given their large impacts on biofuel carbon intensity. Second, emissions from SOC change largely depend on climate conditions according to the results generated from the RothC model (Rothamsted carbon model, see section methodology). In this study, the GHG emissions from SOC change on 1 MJ basis tend to be higher in colder and dryer regions. For example, the mean GHG emissions from SOC change in scenario 1 (GC1 with lower annual temperature 11.7°C and precipitation 1,154.9 mm) is 13.2 $gCO_2e\ MJ^{-1}$, which is 14.7% higher than scenario 2 (GC1 with higher annual temperature 16.5°C and precipitation 1,527.4 mm). This phenomenon is further demonstrated by scenario 7 and scenario 8 where the climate condition is SSP5-RCP8.5 in the year 2050 and SSP5-RCP8.5 in the year 2100, respectively, with higher temperature and precipitation than scenario 5. The mean GHG emissions from SOC changes are 14.9 $gCO_2e\ MJ^{-1}$ in scenario 5, higher than 11.1 $gCO_2e\ MJ^{-1}$ in scenario 7 and 8.8 $gCO_2e\ MJ^{-1}$ in scenario 8. More details for climate conditions are available in section methodology and Table S3. For lower decay rates due to lower temperature and precipitation, reducing the same amount of residue carbon input has a larger reduction of undecayed SOC (as part of soil carbon stock) than higher decay rates and, further, has a larger impact on SOC loss. Hence, lower temperature and precipitation that slows SOC decay can increase the relative change in SOC due to residue removal. The total SOC loss shown in Figure 3A is the result across 100 years, whereas the SOC fluctuates over time with gains and losses within the 100-year time frame (see Figures S1 and S2; see Figure S3 for percentage changes). The spike of SOC content at the beginning of each rotation shown in Figures S1 and S2 is caused by the addition of residues and roots to the litter pool after harvesting at the end of year 1 of each rotation.

Furthermore, the mean life cycle GHG emissions of biofuels without CCS is reduced from 43.1 $gCO_2e\ MJ^{-1}$ in the energy beneficial case to 22.7–25.5 $gCO_2e\ MJ^{-1}$ in the carbon beneficial case. With CCS, the mean life cycle GHG emissions reduce from −68.1 to −71.2 $gCO_2e\ MJ^{-1}$ if biochar is utilized as a soil amendment. In the energy beneficial case, biochar is combusted to generate power that replaces grid electricity (GHG emissions are estimated based on the current market electricity mix); in the carbon beneficial case, biochar as a soil amendment has over 76% carbon mass remained after 100 years (see section methodology) and results in much lower GHG emissions. Hence, choosing biochar for soil applications as stable carbon storage is more climate beneficial, which is consistent with previous literature on biomass pyrolysis.[15,48]

Including emissions from SOC, forest-residue-derived biofuels in the energy beneficial case may not pass the RFS that requires a 60% reduction of GHG emissions of baseline gasoline (37.2 $gCO_2e\ MJ^{-1}$ for renewable gasoline shown as green dashed line in Figure 3A).[46] The mean values of the energy beneficial case biofuel across eight scenarios without CCS are 51.9–58.1 $gCO_2e\ MJ^{-1}$ (P5-P95 values are 38.0–70.1 $gCO_2e\ MJ^{-1}$). Using biochar as a soil amendment decreases GHG emissions, 34.3–38.6 $gCO_2e\ MJ^{-1}$ (P5-P95 values are 15.2–57.2 $gCO_2e\ MJ^{-1}$), increasing the probability of passing the RFS. According to the US EPA, the life-cycle GHG emissions of biofuel from various feedstocks and pathways vary from −29.0 to 117.0 $gCO_2e\ MJ^{-1}$, including the GHG emissions caused by land-use change.

Biofuel from forest residues in this study show lower GHG emissions than some biofuels, e.g., biodiesel from canola oil (48.1 $gCO_2e\ MJ^{-1}$) and ethanol from grain sorghum (46.4 $gCO_2e\ MJ^{-1}$),[46] when SOC changes are not included but higher GHG emission than them when forest SOC changes are considered.

Another conclusion is that forest productivity and management strategies also have an impact on the GHG emissions caused by SOC changes on 1 MJ basis. Comparing scenarios 2 and 4 or scenarios 3 and 5 shows the impacts of forest productivity and management practices on the GHG emissions caused by SOC change (9.4%–11.3% differences). In the energy beneficial case, blue bars in Figure 3A are almost the same across all the scenarios due to the small contribution of forest operation emissions and the same amount of biogenic carbon uptake as shown in Figure 3C (producing 1 MJ biofuel uses the same amount of forest residues). In the carbon beneficial case, blue bars in Figure 3A vary slightly due to the differences in biochar decay emissions, as shown in Figure 3C, which are driven by climate conditions and forest management practices (residues removed at different times lead to different time periods of decay). More details are available in Note S2.

Figure 3B shows the increased impacts of SOC on life cycle GHG emissions of biofuels in shorter analysis time frames in scenario 5 (the results of other scenarios are in Figures S4 and S5). This is mainly caused by faster SOC decrease in earlier years after the residues are collected for biofuel production. The non-linear dynamics of SOC are consistent with the previous LCA of biofuel derived from collecting agricultural residues on cropland.[28] Although SOC-related GHG emissions vary by time frame, the comparative conclusions among different scenarios within the same time frame do not change.

Dynamic carbon flows of forest land over 100 years

Given the similarity among the results of different scenarios, Figure 4A shows the dynamic carbon flows in scenario 6-energy beneficial case (see Data S1 in section data and code availability for the source data). Biogenic carbon uptake by logs is not shown in this figure as it is outside the system boundary. The blue line in Figure 4A shows accumulative GHG emissions from litter and mineral soil, due to the litter decay and change of carbon pools in mineral soil, which is not the net GHG balance of soil and does not imply that soil is a net source of GHG to the atmosphere. The net GHG balances of soil over 100 years include both emissions (blue line) and carbon inputs from the litter (green lines for the biogenic carbon uptake by litter), including litterfall, roots, and uncollected residues. For example, soil is a net carbon sink instead of a net source of GHG emissions for the all-decay case under scenario 1 over 100 years (see Table S4). Figure 4B shows smaller carbon stock changes in mineral soil than in the litter pool (see Data S1 in section data and code availability for the source data). The substantial declines of carbon stock in the litter pool after logging or thinning indicate large litter carbon loss either to the atmosphere or to the mineral soil pool. In Figure 4A, emissions by biofuel production and distribution have stepwise increases when forest residues are removed in the years of precommercial thinning and logging. Hence, it is important to consider SOC change during biomass production when biofuel production introduces disturbance to SOC (e.g., changing carbon input to soil due to residue removal, changing forest management strategies due to biofuel demand).

Net GHG emissions of counterfactual scenarios

Leaving forest residues on-land or pile burning are common practices, which are analyzed as counterfactual scenarios.[30] The total and breakdown 1-ha results of different scenarios are presented in Figures 5A and 5B, respectively. Without the benefits of substituting counterpart fossil fuels (shown as net excluding biofuel

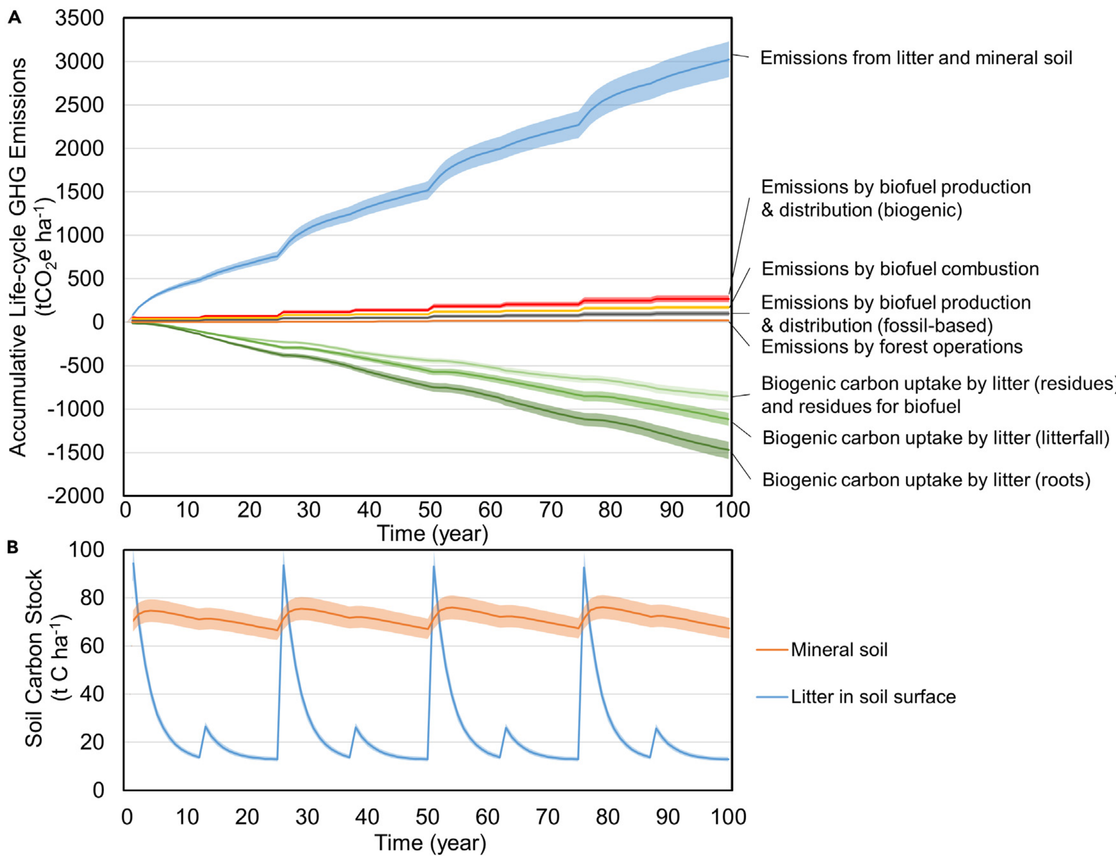

Figure 4. Accumulative life cycle GHG emissions and soil organic carbon stock change of 1-ha forest land over 100 years

(A) Accumulative life-cycle GHG emissions.

(B) Soil organic carbon stock change. Positive values represent the GHG emissions from different sources. Negative values represent biogenic carbon uptake by different biogenic carbon pools. Shaded areas were plotted based on the range of P5–P95 (5th–95th percentile). Solid lines depict mean values in each year. The shaded area of litter in the soil surface in (B) is small to view. Biogenic carbon uptake by logs is not included in this figure.

substitution in Figure 5A), all-decay cases (mean value −16.7–19.3 $tCO_2e\ ha^{-1}$) reach lower total life cycle GHG emissions than pile burning cases (mean value 26.9–62.1 $tCO_2e\ ha^{-1}$) and biofuel cases without CCS (mean value 41.0–151.5 $tCO_2e\ ha^{-1}$ in scenarios 1–8) but higher than biofuel cases with CCS in scenario 9 (mean value −117.0 to −123.7 $tCO_2e\ ha^{-1}$). However, when potential substitution benefits of biofuel (mean value 67.1–205.1 $tCO_2e\ ha^{-1}$) are considered, the biofuel cases in all scenarios are better than all-decay cases (shown as red diamonds in Figure 5A). Hence, whether biofuel is the most carbon beneficial option for land-based forest residue management relies on the effects of biofuel to replace fossil fuel. The substitution effects have large uncertainty, depending on market and policy factors, such as supply and demand elasticity and regional fuel policies.[49] Another conclusion is that converting forest residues to biofuel in warmer and more humid regions has larger benefits to avoid decay emissions than in colder and drier regions if the forest soils are rich enough to maintain forest growth with removing forest residues.[50] For example, converting forest residues to biofuel avoids 3.6 $tCO_2e\ ha^{-1}$ in all-decay case in scenario 1, whereas in scenario 2, with warmer and more humid conditions, this benefit becomes 7.6 $tCO_2e\ ha^{-1}$ in scenario 2 all-decay case.

Forest site productivity and management strategies show larger impacts on 1-ha results in Figure 5 than their impacts on 1 MJ biofuel results in Figure 3. For example,

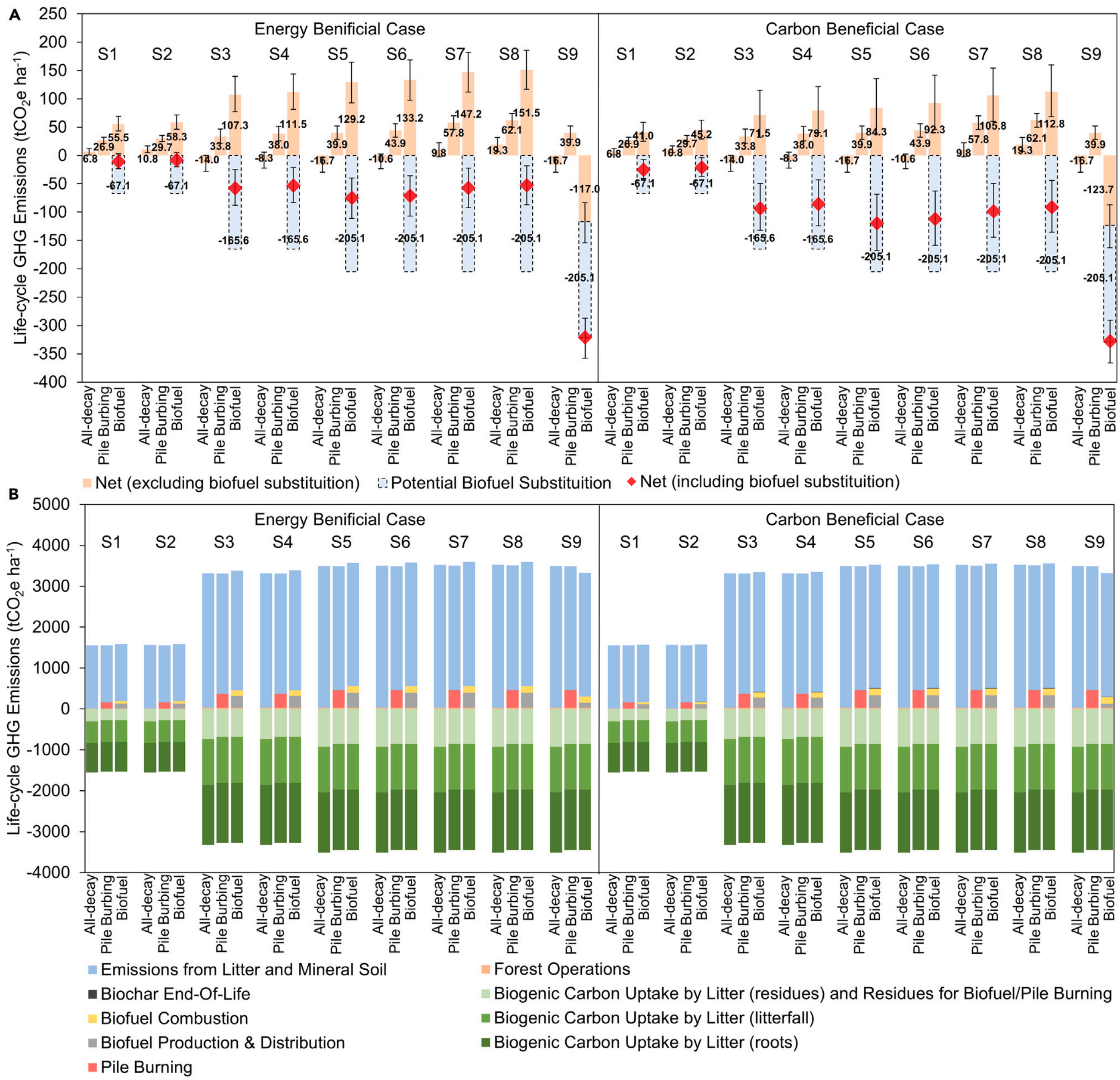

Figure 5. Life cycle GHG emissions on 1-ha basis

(A) Net GHG emissions on a 1-ha basis and potential benefits of biofuel by substituting fossil fuel.

(B) Result breakdown (mean value) of each life cycle stage (not including biofuel substitution). The energy beneficial case combusts biochar to generate power, whereas the carbon beneficial case applies biochar as a soil amendment. S1: low site productivity and lower annual temperature and precipitation; S2: low site productivity and higher annual temperature and precipitation; S3: high site productivity and lower annual temperature and precipitation; S4: high site productivity and higher annual temperature and precipitation; S5: high site productivity with precommercial thinning and lower annual temperature and precipitation; S6: high site productivity with precommercial thinning and higher annual temperature and precipitation; S7: S5 with climate change condition of 2050; S8: S5 with climate change condition of 2100; S9: carbon capture and storage implemented in S5. Error bars represent the P5–P95 range of MCS.

In (A), net life cycle GHG emissions, including potential biofuel substitution (shown as red diamonds), are equal to the summation of life cycle GHG emissions and the potential biofuel substitution benefits.

scenario 2 has 47.7% lower GHG emissions than scenario 4 in the biofuel energy beneficial case (excluding substitution) in Figure 5A, which decreases to less than 2% in Figure 3A. This result is consistent with previous LCAs that show different impacts of forest management on the life cycle GHG emissions when the functional unit is changed from 1 ha of land to 1 unit of forest product.[41] These observations demonstrate the importance of considering forest productivity and management strategies for simultaneous carbon management of forest and biofuel production systems.

In Figure 5B, the breakdown of each life cycle stage (source data are available in Table S4) is shown on a 1-ha basis, excluding the potential biofuel substitution benefits. The summation of the bars in Figure 5B is equal to the net values, excluding the potential biofuel substitution in Figure 5A. Figure 5B shows that emissions from litter and mineral soil account for 84.5%–99.3% (mean value) of the GHG emissions across all the scenarios over 100 years. Furthermore, when collecting forest residues for biofuel, the net GHG balances of soil (emissions from litter and mineral soil minus the CO_2 uptake by the litter fed into soil, i.e., litterfall, roots, and uncollected residues) increase over 100 years, indicating the SOC loss due to forest residue collection for biofuel compared with the all-decay case. For example, in scenario 1 (see Table S4), the net GHG balances of biogenic carbon uptake and emissions from litter and mineral soil in the all-decay case are -8.6 tCO_2e ha^{-1} by mean value and thus +2.3 t C ha^{-1} SOC change; the net GHG balances in biofuel case are +0.9 tCO_2e ha^{-1} by mean value and thus -0.3 t C ha^{-1} SOC change. Therefore, compared with the all-decay case, SOC in the biofuel case decreases by +2.6 t C ha^{-1} by mean value. Detailed data of SOC change in all scenarios are documented in Data S2 (see section data and code availability).

In addition, on a 1-ha basis, the GHG emissions by pile burning are comparable to biofuel production, distribution, and combustion (BPC), as shown in Figure 5B. For example, in the scenario 3 energy beneficial case, BPC emits 426.3 tCO_2e ha^{-1} by mean value, whereas pile burning emits 355.4 tCO_2e ha^{-1} by mean value. However, the biofuel case has the GHG benefit by substituting fossil fuels. Hence, pile burning is not the best choice from the perspective of GHG emissions. Other aspects related to pile burning should be considered in future research, such as their impacts on ecosystem services and water and soil quality.[37–40]

DISCUSSION

In this study, we developed a dynamic LCA to analyze the impact of SOC changes caused by forest residue removal on the total life cycle GHG emissions of biofuel derived from pine residues. This analysis integrated process models of forest and biorefinery with the SOC model, and explored the impacts of varied forest productivities, management strategies, climate conditions, and residue end-of-life. The results show substantial impacts of SOC changes. The RothC results of SOC change in all scenarios are validated by comparing our results with three meta-data analyses that contain field data and have similar combinations of forest management and residue removal strategies.[20,23,51] Overall, the percentage changes (-11.1% to -2.5%) in SOC in the forest floor and topsoil (<30 cm) of the biofuel case (stem harvest with 50% residue removal) relative to the all-decay case (bole-only harvest) over different time periods in this study are within the ranges (-15% to -0.1%) estimated by the three analyses that compared the SOC content in forest floor and topsoil following whole-tree harvest plus forest floor removal with bole-only harvest. Detailed comparisons are discussed in Note S3.

From the perspective of 1-MJ biofuel, the mean GHG emissions caused by SOC change over 100 years are 8.8–14.9 $gCO_2e\ MJ^{-1}$. Without CCS, all other life cycle stages account for 43.1 $gCO_2e\ MJ^{-1}$ if biochar is combusted for power generation, which decreases to 22.7–25.5 $gCO_2e\ MJ^{-1}$ if biochar is utilized as a soil amendment. With CCS, all other life cycle stages account for -68.1 $gCO_2e\ MJ^{-1}$ if biochar is combusted for power generation, and -72.1 $gCO_2e\ MJ^{-1}$ if biochar is utilized as a soil amendment. Hence, the GHG emissions caused by SOC change over 100 years due to forest residue removal averagely account for 20.3%–65.9% of the life cycle GHG emissions of biofuels without CCS and -20.9% to -20.0% with CCS. This impact of SOC change increases with a shorter analysis time frame, but the comparative conclusions across scenarios remain the same regardless of time frames. The GHG emissions by SOC change rely on the climate conditions (e.g., temperature and precipitation), which determine decay rates of varied SOC pools. Removing forest residues in regions with lower temperature precipitation may result in higher GHG emissions from SOC change. The forest management strategies and yield also impact SOC change.

To the best knowledge of the authors, this is the first dynamic LCA study that quantitatively investigates the significance of SOC changes in terms of life cycle carbon emissions for biofuels derived from forest residues. Our results reveal the importance of including soil carbon assessment in biofuel LCAs and policymaking even when forest residues are sourced from sustainably managed forests and no land-use change is involved. Previous literature and current low-carbon fuel policies have primarily focused on GHG emissions related to land-use change for biofuel[52,53] and assumed no SOC changes during biomass production, especially for biomass residues such as forest residues.[23] Although the GHG emissions of SOC change caused by removing forest residues may be smaller than that from land-use change or removing crop residues (which depends on biomass feedstock, prior land-use history, and time horizon, see Note S3 for a detailed discussion), this study demonstrates the potential SOC loss that may reduce the carbon benefit of forest residue-derived biofuel even if no land-use change is involved, and thus affects the comparison between forest residues and other biomass pathways. In addition, the impact of SOC change on the biofuel carbon intensity depends on climate, forest management practices, and analysis time frame, therefore it is important to account for the variabilities of forest sites in future dynamic LCA.

From a land management perspective, using forest residues to produce biofuel shows lower net GHG emissions than leaving forest residues unmanaged or pile burning, if the substitution benefit is included. This benefit is largely constrained by how much fossil fuel can be replaced by biofuels, which requires further investigation of energy market dynamics.[19,54] On a 1-ha basis, forest growth and climate conditions have determining impacts on the life cycle GHG emissions. Although such impacts are diminished when the functional unit is changed from 1 ha of land to 1 MJ of biofuel, climate conditions and forest management still largely affect SOC changes. This indicates the importance of considering climate differences and forest management strategies for simultaneous carbon management of forest lands and biofuel production systems. As this study focuses on understanding the impacts of SOC changes and how the interactions between soil and other carbon pools affect the carbon intensity of biofuels, a stand-level analysis was chosen, which provides an in-depth understanding of interactions between different carbon pools and carbon dynamics of sequential events (e.g., plantation and thinning).[55] A landscape-level analysis investigates a much larger scale of forest land to present the overall carbon fluxes and stock equilibrium of the forest system and commonly averages the carbon pools for trees in various stages of growth cycles.[56,57] Future search can leverage the results of this study to investigate the landscape-level analysis with forestland at various ages, site productivities, and management intensities.

The results presented in this study highlight the importance of including soil carbon assessment in regional and national climate policies related to biofuels derived from biomass residues. The impacts of harvesting and various forest management on soil carbon should be carefully assessed on a case-by-case basis to determine regional-specific strategies to minimize disturbance on SOC (e.g., determine optimal forest residue removal percentage), and maximize the climate benefits of utilizing forest residues for biofuel production. Although this study focuses on the Southern US, the dynamic LCA framework can support spatially explicit analysis for other regions.

This study has a few limitations. Simulating SOC dynamics has uncertainties from different sources, including model structure, uncertain parameters,[58–60] and limited knowledge of the complex interactions among different parameters (e.g., the interaction between temperature and moisture[61]). RothC as a classic model conceptually defines five sub-pools of SOC that are challenging to be measured and validated in real soils.[60] It has a relatively simple model structure with low input data requirements.[58] Although this study does not evaluate the model uncertainty of different soil carbon models, previous studies pointed out the potential benefits of using simpler models (e.g., higher model adaptability,[62] less uncertainty,[58] fewer data availability issues[58]) and the need to balance model complexity and diverse model structures to ensure the model confidence.[59] Advances in process-based land-surface models, such as the Community Land Model (CLM)[63] as a component of Earth System Models (ESMs), and dynamic vegetation models, such as the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ),[64] can achieve more realistic simulations of forest ecosystem and SOC dynamics at stand level when species-specific parameters are available.[60,65–67] Future research can make substantial improvements by selecting the most representative model structures, constraining model parameters, and prescribing external forcings when reliable observational data are available.[60] One limitation of the RothC model is that it cannot simulate the effects of soil disturbance, such as ploughing before the seedling of loblolly pine plantation, which might negatively affect SOC stock with the whole-tree harvest method.[68] This study does not include this effect, considering the following reasons: (1) there is a lack of quantitative evidence for SOC losses due to soil disturbance in the next 25 years of loblolly pine plantation following soil preparation, (2) most reported effects of soil disturbance on SOC do not differentiate between the effects caused by ground preparation, drainage, or the horizontal and vertical displacement of the organic layer within the soil profile,[68] (3) the 50% of residues left on soils in this study might result in less negative impacts on SOC stock compared with whole-tree harvest. Another limitation is that this study does not consider the indirect impacts of pile burning on SOC stock, such as SOC losses due to increased soil temperature caused by pile burning. Excluding these effects in SOC modeling might overestimate SOC stock; however, it will not change the comparative conclusions across all scenarios. In addition, this study does not consider the impacts of increased atmospheric CO_2 concentrations associated with future climate change on forest growth due to the lack of data and evidence to model such impacts in the study region at a stand level.[69–74] One study found that the relative change in net primary productivity of loblolly pine plantations in the Southeastern US against baseline climate conditions (1975–2005) is 0%–10% under RCP 8.5 (2025–2049) and 10%–20% under RCP 8.5 (2075–2099) climate change conditions for a location that has similar baseline mean annual temperature (16.1°C) and site index (27.4 m) as the site in scenario 6 in our study.[73] More data are needed to simulate the impact of future climate change on forest growth at different sites. This study explores CCS as one biorefinery decarbonization strategy. Future research can leverage the dynamic LCA modeling framework presented in this research to investigate more technology improvement opportunities in the future.

Conclusions

In this study, we integrated dynamic LCA with the SOC model and process models of forest and biorefinery to analyze the impact of SOC changes caused by forest residue removal on the total life cycle GHG emissions of forest residue-derived biofuel. The GHG emissions by SOC changes over 100 years are on average 8.8–14.9 gCO_2e MJ^{-1}. All other life cycle stages account for 43.1 gCO_2e MJ^{-1} without CCS and −68.1 gCO_2e MJ^{-1} with CCS if biochar is combusted for power generation, which decreases to 22.7–25.5 gCO_2e MJ^{-1} without CCS and −71.2 gCO_2e MJ^{-1} with CCS if biochar is utilized as a soil amendment. The impact of SOC increases with shorter time frames and tends to be larger in regions with lower temperature and precipitation. Future climate change tends to lower GHG emissions by SOC change. The forest management strategies and yield also impact GHG emissions by SOC change. From the stand-level forest management perspective, utilizing forest residues for biofuel is more climate beneficial than on-land decay or pile burning. This climate benefit depends on fossil fuel substitution and forest site conditions. Our results emphasize the importance of considering forest soil carbon assessment in biofuel LCAs, policymaking, and forest management, even when forest residues are utilized without land-use change.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Please contact the lead contact Dr. Yuan Yao (y.yao@yale.edu) for information related to the data and code described in the following experimental procedures section.

Materials availability

No materials were used in this study.

Data and code availability

All original data have been deposited and are publicly available at Zenodo: https://doi.org/10.5281/zenodo.10268498. Any additional information required to reanalyze the data reported in this paper is available in this paper's supplemental information and available from the lead contact upon request.

Methodology

LCA framework

In this study, a cradle-to-grave dynamic LCA integrates the forest growth model, forest SOC model, biorefinery process model, and MCS. The growth and yield data simulated by the forest growth model were used to quantify the carbon uptake from the atmosphere and carbon in biomass. SOC change in varied site productivity cases and management strategies were simulated by RothC.[75] The process model was built in Aspen Plus (see process flow diagram in Figure S6) to quantify GHG emissions and the effects of biomass composition variations (i.e. carbon, moisture, and ash content).[76] A MCS was conducted to understand the impacts of uncertainties in the key parameters. The functional unit is 1-MJ biofuel produced. The results on a 1-ha basis over 100 years are also displayed to provide insights on forest land management. Life cycle inventory (LCI) data are compiled on a year-by-year basis to reflect the temporally dynamic profile of GHG emissions and biogenic carbon uptake.[77] Different GHGs are converted to CO_2e using the GWP-100 (Global Warming Potential for the 100-year time horizon) factors by the Intergovernmental Panel on Climate Change (IPCC) AR6 report.[78] Other metrics (e.g., global temperature potential and dynamic GWP) can be used based on the dynamic LCI presented in this study.[78–80]

Forest growth and yield

The aboveground forest growth and yield of loblolly pine (*Pinus taeda L.*) adopted the simulation model Plantation Management Research Cooperative (PMRC)[81] combined with aboveground biomass estimation functions developed for loblolly pine in the Southern US.[82] To assess the impacts of varied site productivities and forest management practices, three growth cases (GC1–GC3) were developed (as shown in Table S5). The low site productivity is represented by the site index (in the unit of feet) of 60 in GC1 at the age of 25 years, whereas the site index of the high site productivity is 90 in GC2 and GC3 at the age of 25 years. To explore the impact of thinning, GC1 and GC2 do not have thinning, whereas GC3 has precommercial thinning in year 12. Precommercial thinning offers the benefits of preventing stagnation, increasing stem volume, decreasing the mortality due to insects (e.g., pine beetle), and potential revenue by selling residues.[83–85] In this study, the forest is sequentially replanted with a 25-year rotation. The baseline case is the all-decay case. For the other two cases, the analysis starts from forest residue collection in the final year of the previous rotation.[86] To model the negative impact of removing residues on tree growth in biofuel and pile burning cases, this study adopts the −3.1% for each rotation after removing residues (e.g., −3.1% for the first rotation after removing residues, −6.1% for the second rotation after removing residues) based on the meta-analysis study by Achat et al.[42] Pile burning may also impact tree growth, which can vary by time (short or long term), tree species, soil conditions, climate conditions, and geospatial locations.[87–90] Future research should consider this impact given the data availability. More details about aboveground forest growth and yield modeling and the three growth cases are in Note S4.

Forest operations

The forest operations in this study contain site preparation, planting, applying fertilizers and herbicides, precommercial thinning, logging, and chipping (only for the biofuel case). All the biomass generated from the precommercial thinning are treated as residues due to their non-merchantable sizes. Logging yields both logs (under bark) and residues. The mass fraction of residues is assumed to be 19%–25% of the aboveground standing biomass based on the literature,[91] the rest of which are logs. The mass fraction of collectible residues is assumed to be 50% for biofuel case, according to the literature.[7,33–36] The allocation problem is reduced by dividing the processes of forest operations into detailed sub-processes between two products, logs and collected residues, in the biofuel case.[92] Specifically, only precommercial thinning and chipping residues are attributed to forest residues for biofuel production. In all-decay and pile burning cases, log is the only product of the forest system, implying that other tree compartments (i.e. branches, needles, stump, and roots) are left in forests (hereafter referred to as uncollected residues) and are consequently considered as necromass in the simulations. Additionally, the study tests the mass allocation method that does not show large impacts on the results of 1 MJ basis (see Note S2 for the results). All the upstream GHG emissions of production and transportation of fuels, electricity, and chemicals used in forest operations are included. The details of the forest operation schedule and LCI data are available in Note S5 and Tables S6 and S7.

Forest biomass decay and SOC change

The SOC change over 100 years was simulated by RothC (see the model structure in Figure S7), which has been widely used for cropland, grassland, and forestland.[75,93–100] The performance of the model has been compared with other models[58,93,98] and validated in previous studies with measured data.[93–98] For example, the simulated values by RothC from one study that simulated SOC change for the southern pine in the US are within the standard error of the measured values at the beginning and end of the experiment.[93] They also compared different soil carbon models and concluded that RothC had a better performance.[93] Another study observed a strong correlation between the simulated results and measured data indicated by Pearson's r value of 0.997 for temperate continental forest.[94] A root-mean-square error (RMSE) value of 12.76 was estimated for RothC in a UK forest site, indicating a reasonable fit to measured SOC data.[98] A study that evaluated the performance of RothC in Mexican forests indicated a high fit to observed SOC data with statistic values of 0.96 for Pearson's r, 0.21 for RMSE, 0.9 for model efficiency, and 0.1 for relative error.[96] Overall, the observations from previous studies show a good agreement between simulated results and measured data for forest. The results simulated by RothC sit in the middle of the range simulated by all other models, such as Yasso07, CENTURY, Forest-DNDC, Q, CoupModel, and ROMUL.[58]

In this study, the model was run on a monthly time step with inputs including monthly carbon inputs, monthly climate condition data, and soil condition data. The uncollected residues (100% for all-decay case and 50% for biofuel/biochar case) and root biomass from thinning and logging, along with annually generated litterfall, are the carbon input sources to the SOC. The carbon input to RothC is calculated based on the carbon contents of the input litter derived from the forest growth model, including uncollected residues from precommercial thinning and logging, coarse root biomass from precommercial thinning and logging, annually generated dead fine root biomass, and annually generated litterfall (see Note S4). The data of annual carbon input to the soil used in RothC are documented in Data S2 (see section data and code availability). The total SOC pool defined in this study consists of a litter carbon pool in soil surface and a carbon pool in mineral soil, according to previous studies.[23,94,101]

This study selected four sites with two different climate conditions (climate conditions 1 and 2) varied by geospatial location and two extreme climate change conditions (1-year data of 2050 under SSP5-RCP8.5 and 1-year data of 2100 under SSP5-RCP8.5 from the Energy Exascale Earth System Model [E3SM]).[102–105] The 30-year (1991–2020) mean monthly climate condition data (e.g., mean temperature and precipitation) were derived from the CRU TS 4.05 dataset for climate condition 1 and 2.[106] The site for scenario 1 (with a site index of 60 for GC1) is in northeastern Tennessee with an annual precipitation of 1,154.9 mm and an annual mean temperature of 11.7°C (climate condition 1). Scenarios 3, 5, and 9 are located in a nearby location with the same climate conditions as scenario 1 but a different site index 90 for GC2 and GC3. The site for scenario 2 (with a site index 60 for GC1) is in northern Alabama with annual precipitation of 1,527.4 mm and an annual mean temperature of 16.5°C (climate condition 2). The site for scenarios 4 and 6 is located nearby with similar climate conditions as scenario 2 but a different site index 90 for GC2 and GC3. Scenarios 7 and 8 share the same location and growth rate as scenario 5 but consider future climate changes with SSP5-RCP8.5 in the year 2050 and SSP5-RCP8.5 in the year 2100, respectively. More details about site conditions are available in Tables S1 and S3. The soil condition data (e.g., soil clay content, SOC content, and soil depth) were collected from ISRIC-World Soil Information.[107] The output of the

SOC model includes the annual CO_2 emission and SOC content in each year simulated.[75] More details are available in Note S1 and Tables S1, S3, and S8.

Biomass transportation

After pine residues are chipped on-site, the chips are transported to the biorefinery by trucks. A transportation distance 135 km is used, based on the literature data for a 2,000 oven dry t per day biorefinery producing biofuel from pine residues in the Southeastern US.[108] The transportation GHG emission data are from the ecoinvent database.[109]

Biomass conversion

The fast pyrolysis biorefinery model was built in Aspen Plus based on the model by Ou et al.[110] The process flow diagram is shown in Figure S6. In the biorefinery, pine residues are first pretreated by drying (reaching moisture content 9% [wet basis]) and size reduction (2.5–3.8 mm).[43] Then pine residues go through fast pyrolysis and yield pyrolytic vapors and biochar. The pyrolytic vapors are quenched to derive bio-oil and NCG. The bio-oil is further hydrotreated using hydrogen from steam reforming to upgrade to hydrocarbons and distilled into gasoline- and diesel-range products.[16] In this study, the NCG and other off-gas are the energy sources for the combined heat and power (CHP) plant. For biochar, this study includes two end-of-life cases. The energy beneficial case maximizes energy output by combusting biochar for energy generation in the CHP. The carbon beneficial case minimizes GHG emissions by utilizing biochar as soil amendment.[47,111] The average carbon mass in biochar is 0.119 t per dry t forest residue input. Hence, in the energy beneficial case, the biogenic carbon uptake of residues is all released by biofuel production (combusting NCG, off-gas, and biochar) and biofuel combustion. In the carbon beneficial case, the biogenic carbon uptake of residues is partially released by biofuel production (combusting NCG and off-gas), biofuel combustion, and biochar decay, and the rest is stored in biochar. More details are in Note S6. Because the CHP releases CO_2 emissions, this study includes a case of implementing CCS in the biorefinery. The corresponding LCI data of CCS, including CO_2 capture, CO_2 transport, and CO_2 storage, are collected from the literature (more details are available in Note S6 and Table S9). The average energy efficiency of the biorefinery, estimated as the energy output (biofuel, biochar, and electricity) divided by energy input (forest residues, natural gas, electricity, and diesel), is 36.4% in energy beneficial case and 37.5% in carbon beneficial case.

This study unitized MCS to examine the impacts of biomass composition variations (i.e., carbon, moisture, and ash content as shown in Table S7). Given the high computational cost of Aspen Plus simulations, a surrogate model was established using Artificial Neural Network based on the inputs and outputs of the Aspen Plus model (see Note S7, Tables S10 and S11) to allow for computationally efficient MCSs.

End-of-life of biofuel and biochar

The biofuels, diesel, and gasoline are distributed to the market and combusted by vehicles. The GHG emissions of biofuel distribution were collected from GREET 2021 for conventional diesel and gasoline distribution.[112] The emission factors of fuel combustion in the internal combustion engine adopted the data from the literature.[113] GHG emissions of biochar decay after application as a soil amendment is modeled based on a three-pool exponential decay function.[114] The details are documented in Note S8 and Table S12.

Pile burning

An alternative method of residue disposal is pile burning on the open site, including activities of collecting, piling, and burning.[37] Pile burning is a common method for treating forest residues and preparing the site for replanting.[37–40] In this study, to make a fair comparison, the mass fraction of pine residues collected for pile burning is assumed to be the same as the biofuel case, 50%.[7,33,115] Pile burning could increase soil temperature, consequently, increase SOC losses.[68] This study does not consider this effect for the following reasons: (1) pile burning only affects a limited number of sites rather than the whole land area as scattered residues are often collected and piled up at a centralized location, although there may be several piles at multiple sites, and (2) it is very challenging to quantify the SOC losses with soil models as the temperature increase caused by burning is rapid and temporary. The fuel consumption of pile burning was collected from literature and shown in Table S6.[116]

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2023.12.018.

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AUTHOR CONTRIBUTIONS

Y.Y. and K.L. designed the idea. Y.Y. supervised this study. K.L. collected and analyzed the data related to forest growth, biomass conversion, end-of-life cases of forest residues, and processed and plotted the results. B.Z. simulated and analyzed forest soil organic carbon change. K.L. and T.L. conducted the LCA. K.L., B.Z., and Y.Y. wrote the draft. All the authors contributed to writing and editing the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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