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Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels

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The potential of forest-based bioenergy to reduce greenhouse gas (GHG) emissions when displacing fossil-based energy must be balanced with forest carbon implications related to biomass harvest. We integrate life cycle assessment (LCA) and forest carbon analysis to assess total GHG emissions of forest bioenergy over time. Application of the method to case studies of wood pellet and ethanol production from forest biomass reveals a substantial reduction in forest carbon due to bioenergy production. For all cases, harvest-related forest carbon reductions and associated GHG emissions initially exceed avoided fossil fuel-related emissions, temporarily increasing overall emissions. In the long term, electricity generation from pellets reduces overall emissions relative to coal, although forest carbon losses delay net GHG mitigation by 16–38 years, depending on biomass source (harvest residues/standing trees). Ethanol produced from standing trees increases overall emissions throughout 100 years of continuous production: ethanol from residues achieves reductions after a 74 year delay. Forest carbon more significantly affects bioenergy emissions when biomass is sourced from standing trees compared to residues and when less GHG-intensive fuels are displaced. In all cases, forest carbon dynamics are significant. Although study results are not generalizable to all forests, we suggest the integrated LCA/forest carbon approach be undertaken for bioenergy studies.

Introduction

Forests can contribute to greenhouse gas (GHG) mitigation strategies through capturing and storing atmospheric CO_2 in live biomass, dead organic matter, and soil pools, supplying a source for wood products that both stores carbon and can displace more GHG-intensive alternatives, and providing a feedstock for bioenergy to displace fossil fuel use. While the merit of each of these options has been individually investigated, trade-offs associated with forest resource utilization decisions must also be considered. Of particular interest is the relationship between harvest and forest carbon storage and how this impacts the GHG mitigation performance of forest products, including bioenergy. Existing tools employed to evaluate emissions associated with different forest resource use decisions are not individually well suited to considering such interactions.

Life cycle assessment (LCA) has been applied to bioenergy options, including electricity generation and transportation fuels. The GHG mitigation potential of bioenergy products depends on activities throughout the entire life cycle (LC), making such a perspective necessary for a comprehensive evaluation. Numerous LCAs have focused on agricultural biomass as feedstock for bioenergy, e.g., reviewed in ref (*1*). Comparatively few LCAs have evaluated bioenergy from forest biomass; those that have examined electricity generation (e.g., ref (*2*)), heating (e.g., ref (*3*)), and transportation (e.g., ref (*4*)). Bioenergy LCAs have generally found that the substitution of fossil fuel-derived energy with biomass-derived alternatives reduces GHG emissions, owing in part to the assumption that biomass-based CO_2 emissions do not increase atmospheric CO_2.

Conventional wisdom has generally accepted this assumption of biomass 'carbon neutrality', and thus, most of the LC GHG emissions associated with bioenergy production are attributed to fossil carbon inputs into the system (*5*). In practice, however, the assumption of carbon neutrality may not accurately represent carbon cycling related to biomass growth (e.g., ref (*6*)). The practice of annual or semiannual harvest in agriculture means that carbon uptake by biomass may reasonably match carbon release in bioenergy systems within a short time frame, although land use change impacts resulting from biomass production can upset this balance (*7*). In temperate forests, the harvest cycle can range from 60 to 100 or more years due to the relatively slow growth of forest species. It could therefore take a century for carbon stocks to be replaced, particularly under a clearcutting regime (harvest of all merchantable trees). Harvest patterns and associated implications for forest carbon stocks vary extensively, ranging from clearcuts to variable retention patterns, including shelterwood and selection cuts. Some variable retention approaches may actually increase forest regeneration, increasing the potential to recover carbon (*8*). Bioenergy production from harvest residues (tree tops and branches) also impacts forest carbon stocks; left uncollected, residues continue to store carbon until released by decomposition or treatment for forest regeneration. While sustainable forest management should ensure that harvest does not impair the long-term productivity of forests, harvest and other forest management activities clearly impact present and future forest carbon stocks. LCA, in its current form, is not well suited to consider the complexities of forest carbon dynamics.

Forest carbon studies have weighed the carbon balance of harvest with the GHG mitigation potential of forest products (e.g., refs *9–11*). Some studies have utilized sophisticated forest carbon models to track changes in carbon stored in living biomass (above ground and below ground), dead organic matter, and soil pools (e.g., refs *12, 13*). These studies, however, generally employ simplified assumptions regarding the GHG emissions of forest products (including bioenergy) and have not incorporated a full LC approach. Given the dependence of emissions on specific system

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characteristics (e.g., biomass source, bioenergy production process, fuel displaced), generalized assumptions regarding the GHG mitigation potential of bioenergy are inadequate for informing decision making and public policies.

State-of-the-art tools are available for independently evaluating both the LC emissions of bioenergy systems and forest carbon dynamics. Using these methods in isolation, as has been general practice, stops short of the comprehensive evaluation needed to properly assess the GHG emissions of forest products. In an assessment of GHG mitigation performance of structural wood products, ref (*14*) incorporated LCA with an analysis of forest carbon dynamics. While the study did not consider bioenergy as a product, the results illustrate the importance of considering forest carbon and LC emissions simultaneously when evaluating forest products. Applied to bioenergy, integrating LCA with forest carbon modeling would improve understanding of potential contributions to climate change mitigation.

Bioenergy has been treated inconsistently across energy and climate change policy initiatives in terms of how (or if) GHG emissions are quantified. Forest bioenergy policies that ignore carbon flows in the forest may prove ineffective at achieving actual emissions reductions (*15*). Exclusion of forest carbon from current initiatives is in part due to data issues, although emerging guidelines may ameliorate this situation (*16*). Tools that are able to synthesize forest carbon data and LCA and evaluate trade-offs between bioenergy and forest carbon remain to be developed.

Forest bioenergy has the potential to significantly reduce GHG emissions compared with fossil fuel alternatives. However, interactions between biomass harvest and forest carbon and the resulting effect on the GHG mitigation performance of bioenergy systems are inadequately understood. The objectives of this study are to demonstrate the integration of LCA and forest carbon modeling to assess the total GHG emissions (referred to as “emissions”) of forest-based bioenergy options and to determine how emissions reductions associated with bioenergy are impacted when forest carbon is taken into account. We demonstrate this approach through a case study investigating two bioenergy products (wood pellets, referred to as pellets, and ethanol) from two biomass sources (standing trees and harvest residues, referred to as residues) within the Great Lakes−St. Lawrence (GLSL) forest region of Ontario, Canada.

Methods

We develop a framework integrating two analysis tools: life cycle inventory (LCI) analysis and forest carbon modeling. See Supporting Information for additional detail on all methods. LCI analysis quantifies emissions related to the production and use of forest biomass-derived energy. The LCI is based on the assumption of immediate biomass carbon neutrality, as is common practice, and is therefore employed to quantify the impact of all emissions on atmospheric GHGs with the exception of biomass-based CO_2.

Forest carbon modeling quantifies the impact of biomass harvest on forest carbon dynamics, permitting an evaluation of the validity of the immediate carbon neutrality assumption. If biomass-based CO_2 is fully compensated for by forest regrowth, biomass harvest will have no impact on forest carbon stocks. Reduced forest carbon indicates that a portion of biomass-based CO_2 emissions contributes to increased atmospheric GHGs and should be attributed to the bioenergy pathway. The total emissions associated with a bioenergy system are the sum of the two sets of GHG flows (those resulting from the LCI and those from the forest carbon analysis)

$$\mathrm{GHG}_{\mathrm{Tot}}(t) = \Delta\mathrm{FC}(t) + \mathrm{GHG}_{\mathrm{Bio}}(t) \tag{1}$$

where $\mathrm{GHG}_{\mathrm{Tot}}(t)$ is the total emissions associated with bioenergy, $\Delta\mathrm{FC}(t)$ is the change in forest carbon due to biomass harvest for bioenergy, and $\mathrm{GHG}_{\mathrm{Bio}}(t)$ is the GHG emissions associated with bioenergy substitution for a fossil fuel alternative [all reported in metric tonne CO_2 equivlent (tCO_2equiv)] at time t.

The change in forest carbon, $\Delta\mathrm{FC}(t)$, is the difference in forest carbon stocks between harvest scenarios: those ‘with’ and ‘without’ bioenergy production. While we present this as a single parameter in eq 1, in reality forest carbon models consider the complexity of carbon fluxes between pools within the forest and between the forest and atmosphere. Carbon in biomass harvested for bioenergy is assumed to be immediately released to the atmosphere. However, forest regrowth will capture and store atmospheric CO_2 over time. There is therefore a time dependency to the carbon impact of forest harvest for bioenergy. Assessing the change in forest carbon requires consideration of the forest response following harvest and the fate of the biomass source if it is not harvested for bioenergy (standing trees could be harvested for other uses or never harvested; residues could decompose on site, be burned as part of site preparation, or be collected for other uses). Local conditions influence such factors and must inform specific applications of this method. Information relevant to the current case study is provided in the following methods subsection.

LCI quantifies emissions associated with all activities from initial resource extraction and fuel production through to the use of fuels, inclusive of transportation and distribution stages. Emissions related to the production of inputs are included based on their cradle-to-grave activities. Comparing emissions of a bioenergy product with the relevant reference fossil fuel alternative(s) determines the bioenergy GHG mitigation performance. The output of the bioenergy LCI models, emissions per functional unit, is not directly compatible with the output of forest carbon models, which quantify carbon stocks over relatively long time periods (e.g., 100 years) in order to fully capture the impact of management decisions. To integrate the assessment tools, we quantify the cumulative emissions associated with bioenergy production within the time period investigated with the forest carbon model (e.g., 100 years), considering GHG mitigation from fossil fuel displacement to be permanent. LCI results are converted to a quantity of emissions by

$$\mathrm{GHG}_{\mathrm{Bio}}(t) = \int_0^t Q_i(t) \times \mathrm{GHG}_i \, \mathrm{d}t \tag{2}$$

where $\mathrm{GHG}_{\mathrm{Bio}}(t)$ represents emissions associated with bioenergy substitution for fossil fuel alternative(s) at time t (tCO_2equiv), $Q_i(t)$ is the quantity of biomass used to produce bioenergy product i at time t (e.g., oven dry tonne (odt) biomass/year), and GHG_i is the emissions associated with bioenergy product i per unit biomass (tCO_2equiv/odt). Summing the bioenergy emissions (based on the LCI results) and the forest carbon emissions gives the total emissions of bioenergy utilization over time as shown in eq 1.

Considering emissions over a long time period is relevant to the carbon dynamics of a forest; however, this introduces uncertainty regarding future forest conditions, markets, and the performance of the energy systems investigated. The LCI and forest carbon analysis in this research consider that these conditions remain static throughout the time frame due to the difficulty of deriving reasonable estimates for these parameters. These issues are further examined in the Results and Discussion.

Application of LCI/Forest Carbon Model framework. We apply the above framework to investigate the impact of forest carbon dynamics on the total emissions associated with several forest-based bioenergy pathways. Forest biomass is assumed to be procured for the production of fuels for electricity generation and light-duty vehicle (LDV) transportation. Reference models are also developed for conventional fuel sources to which the bioenergy pathways are compared. We examine emissions of selected GHGs (CO_2, CH_4, N_2O), reported as CO_2equiv based on 100 year global warming potentials (*17*). See the Supporting Information for additional case study details and data.

The pathways considered are as follows. (1) Electricity generation: (a) Reference coal: production of electricity from coal at an existing generating station (GS) in Ontario; (b) Pellet cofiring, harvest residue: production of electricity at 20% cofiring rate (energy input basis) at retrofit coal GS, pellets produced from residues; (c) Pellet cofiring, standing tree: production of electricity at 20% cofiring rate (energy input basis) at a retrofit coal GS, pellets produced from standing trees. (2) Transportation: (a) Reference gasoline: gasoline use in LDV; (b) E85, harvest residue: ethanol/gasoline blended fuel use in LDV, ethanol produced from residues (biomass is not pelletized); (c) E85, standing tree: ethanol/gasoline blended fuel (85% ethanol by volume) use in LDV, ethanol produced from standing trees (biomass is not pelletized).

Biomass Sources. Biomass is supplied from standing trees and residues from 5.25 million hectares within the GLSL forest region in Ontario. This area represents 19% of provincially owned forest managed for timber production. Trees allocated for harvest that are not currently utilized for traditional products could serve as a source of biomass for bioenergy applications without impacting markets for conventional wood products. Residues do not have a useful purpose in the region's conventional forest products industry and are left to decompose in the forest. Competition for limited wood resources can result in diversion from current uses (e.g., pulp) to bioenergy (*18*) with potential indirect emissions consequences (*7*). By limiting the present study to biomass sources unutilized for conventional products, we avoid such market interactions.

Standing tree harvest and related forest operations (regeneration, road construction/maintenance, and transport to the pellet/ethanol facility) are assessed using a model developed in our previous work (*6*). Emissions related to residue collection are calculated by treating the residues as a byproduct of forest harvest. Only additional fuel use required for collection beyond that of current harvest operations is allocated to the residues; other forest operations are allocated to the primary forest product and are therefore not included in the present study. Residue collection consists of roadside chipping and loading.

Electricity Pathways. LCI models representing electricity generation from coal and cofiring of pellets from standing trees were developed in our prior work (*6*). The models consider emissions associated with the full fuel LCs from initial resource extraction through to combustion as well as upstream emissions related to process inputs. One kWh is selected as the functional unit for the analysis. We assume that pellet production from residues and their use for cofiring is similar to that of pellets from standing trees but modify the pelletization process to reflect that residues are chipped in the forest (standing trees are delivered as logs). For both sources, 15% of input biomass is assumed to be consumed during pellet production to dry the biomass. Avoiding fossil fuel use reduces emissions during the pelletization process but increases biomass input to pellet production and associated forest carbon impacts. Implications of this assumption are considered in Results and Discussion.

Transportation Pathways. Ethanol production, transportation, distribution, and use as E85 fuel in LDV are modeled based on the wood-to-ethanol biochemical conversion pathway in the Government of Canada's "well-to-wheel" model, GHGenius 3.17 (*4*). The gasoline portion of E85 fuel and the reference gasoline pathway are also taken from GHGenius. The functional unit for the transportation pathways is 1 km driven. Significant uncertainty exists in evaluating ethanol production from cellulosic feedstock as technological development and optimization is ongoing and production not yet at commercial scale (*19*).

Forest Carbon. The forest carbon dynamics related to biomass harvest are evaluated using FORCARB-ON, an Ontario-specific adaptation of the FORCARB2 model (*12*). FORCARB-ON quantifies carbon stocks (in living trees, soil, standing dead trees, down dead wood, forest floor, and understory vegetation pools) based on harvest schedules and inventories that producers are required to report to the Province. Harvest schedules take into account species and age composition of the forest, age classes eligible for harvest, natural disturbance frequency, growth rates, and forest succession. The model estimates forest carbon stocks over 100 years, a time frame relevant to the long-term perspective of forest management planning.

We evaluate forest carbon stocks for three potential harvest scenarios: (1) "current harvest" baseline, where biomass (standing trees, residues) is not collected for bioenergy production and therefore timber is removed solely to satisfy the current demand for traditional wood products; (2) "current + residue" harvest, with residue removal for bioenergy production; and (3) "maximum allowable" harvest, with additional standing tree harvest (compared to the baseline) for bioenergy production (residues are not collected). The difference in forest carbon stocks between the bioenergy production scenarios and "current harvest" baseline scenario is allocated to the bioenergy products. Additional standing tree harvest for bioenergy occurs as scheduled under forest management plans; following harvest, stands are regenerated by planting or natural regeneration, varying by site. If not harvested for bioenergy, standing trees eventually undergo natural succession and are subject to a small likelihood of natural disturbance. Residue collection is assumed to not impact soil carbon stocks; uncollected residues are assumed to decompose on site, either at the roadside or near where trees were felled. The consequence of collecting residues for bioenergy production is that this temporary carbon store is 'liquidated' immediately (combusted during bioenergy production and use) rather than decomposing slowly in the forest. Therefore, the associated change in forest carbon is the difference between immediate release (bioenergy) and decomposition over time if not collected. As noted previously, these factors could vary by location with a potentially significant impact on the assessed forest carbon emissions. We do not consider emissions related to the current harvest for traditional wood products or their use. Under the assumptions in this study, this is not affected by the decision to undertake additional harvest or collect residues for bioenergy production.

Results and Discussion

Life Cycle Inventory Results, Excluding Forest Carbon. LCI results for the pathways are shown in Table 1, using the assumption of immediate biomass carbon neutrality. LCI emissions for biomass are greater when sourced from standing trees than from residues. Upstream (fuel production) stages, however, are minor contributors to LC emissions of either pellets or ethanol. The majority of emissions arise from the combustion of fossil fuels, both as the fossil portion during bioenergy use and in the reference fossil pathways. Excluding changes in forest carbon, 20% pellet cofiring reduces LC emissions by 18% compared to coal-only operation (kWh basis) whether standing trees or residues are utilized, whereas an E85-fueled LDV reduces LC emissions by 57% compared to a gasoline LDV (km-driven basis). The greater emission reduction of E85 relative to pellet cofiring gives the appear-

TABLE 1. Life Cycle GHG Emissions Associated with Bioenergy Product (wood pellets, ethanol) Blended for Use and Substitution for Fossil Reference Pathway[a]

	electricity generation pathways			transportation pathways		
life cycle stage	coal[c,d] (g CO_2equiv/kWh)	20% pellet cofiring, residue (g CO_2equiv/kWh)	20% pellet cofiring, standing tree[c] (g CO_2equiv/kWh)	gasoline[f] (g CO_2equiv/km)	E85, residue (g CO_2equiv/km)	E85, standing tree (g CO_2equiv/km)
forest operations		1.9	4.3		5.1	11.7
bioenergy production, distribution [b]		9.5	9.6		46	46
upstream fossil energy component	62	50	50	77	16	16
fuel use (combustion)[e]	939	760	760	211	48	48
total life cycle emissions	1001	821	824	288	116	123

[a] Values assume immediate carbon neutrality and do not take into consideration forest carbon implications. [b] Includes transport of biomass to the production facility, bioenergy production, electricity coproduct credit from biochemical production of ethanol, and bioenergy transportation/distribution stages. [c] Reference (*6*). [d] Surface coal mining removes biomass and disturbs soil, which results in GHG emissions due to direct land use change. These emissions along with other mining process emissions are considered in our analysis. [e] Fuel use consists of GHG emissions from the fossil component of fuel (coal, gasoline) and non-CO_2 GHG emissions associated with bioenergy (pellet, ethanol) combustion. [f] Reference (*4*).

TABLE 2. Forest Carbon Impacts of Continuous Biomass Harvest

	forest carbon stock change ($MtCO_2$equiv)										
	year										
biomass source	0	10	20	30	40	50	60	70	80	90	100
residues	0[a,b]	−8.2	−11.8	−13.0	−13.5	−13.9	−14.3	−14.7	−15.0	−15.2	−15.2
standing trees	0	−43.6	−80.9	−106.3	−112.5	−113.4	−112.7	−132.8	−143.6	−150.8	−150.7

[a] Negative values indicate a GHG emission source (forest carbon stocks are reduced due to biomass harvest) that is attributable to bioenergy production. [b] Reported values are the total stock change due to continuous harvest. For example, 50 years of continuous standing tree harvest reduces total forest carbon stocks by 113.4 $MtCO_2$equiv.

ance that this pathway represents a preferred use of biomass for reducing emissions, but this results primarily from the cofiring scenario utilizing a lower proportion of biomass fuel (20%, energy basis) than E85 (79%, energy basis).

We convert the LC emissions from their initial functional units (kWh, km driven) to a basis of one odt of biomass removed from the forest for bioenergy production ($odt_{biomass}$). This makes the LCI and forest carbon model results compatible and facilitates a comparison of the two bioenergy pathways (electricity, ethanol) in terms of their effectiveness of biomass utilization in reducing emissions (see Supporting Information, equation S-3). Over their respective LCs, the production and use of pellets from standing trees displaces 1.49 tCO_2equiv/$odt_{biomass}$, while ethanol production and use displaces 0.51 tCO_2equiv/$odt_{biomass}$, exclusive of forest carbon impacts. Utilizing residues as a feedstock for pellets and ethanol displaces 1.50 and 0.53 tCO_2equiv/$odt_{biomass}$, respectively. Substitution of coal with pellets provides a greater mitigation benefit than substitution of gasoline with ethanol, primarily due to the higher GHG intensity of coal. To put these values into perspective, the constituent carbon in biomass is equivalent to 1.83 tCO_2equiv/odt. The significance of releasing this biomass-based CO_2 is considered subsequently.

Forest Carbon Analysis Results: Impact of Biomass Harvest. Sustainable biomass sources in the study area could provide, on average, 1.8 million odt/year from standing trees and 0.38 million odt/year from residues. Combined, these sources could provide 2.2% of annual electricity generation in the province or reduce gasoline consumption by 3.3% (see Supporting Information). Forest carbon loss due to undertaking biomass harvest in the study area over a 100 year period is shown in Table 2. For both sources (residues, standing trees), harvest reduces forest carbon asymptotically toward a "steady state". For standing trees, as more stands are harvested for bioenergy over time, the rate of carbon accumulation in regrowing stands increases toward a point where, under ideal conditions, carbon accumulation balances removals associated with continued harvest. For residues, a similar steady state is eventually achieved when the rate of carbon removals at harvest is matched by the expected rate of residue decomposition if harvest is not undertaken. Continuing biomass harvest once a steady state has been reached would not impact forest carbon stocks; however, initiating biomass harvest beyond current removals has significant emissions consequences in the near to medium term. Forest carbon loss due to harvest residue collection approaches a maximum of ~15$MtCO_2$equiv, whereas standing tree harvest for bioenergy results in a carbon loss exceeding 150 $MtCO_2$equiv after 100 years. Proportional to the quantity of biomass provided, standing tree harvest results in a greater impact on forest carbon than harvest residue collection because live trees would generally continue to sequester carbon if not harvested, whereas carbon in uncollected residues declines over time.

Total GHG Emissions: Combined LCI and Forest Carbon Analysis Results. Summing the cumulative emissions of the bioenergy options (LCI results Figure 1, dashed lines) and the forest carbon emissions (Figure 1, dotted lines) results in the total emissions of bioenergy production and use (Figure 1, solid lines). When reductions in forest carbon are included, emission mitigation is delayed and reduced compared to the case where immediate biomass carbon neutrality is assumed. For all scenarios investigated, total emissions from the bioenergy pathways initially exceed those of the reference fossil fuel pathways, indicating an initial increase in emissions resulting from bioenergy use. Emissions associated with forest carbon loss due to biomass harvest exceed the reduction of fossil fuel-based emissions provided by bioenergy substitution. The emissions increase associated with bioenergy, however, is temporary: the rate of forest carbon loss decreases with time, whereas the emissions reduction associated with utilizing bioenergy in place of fossil alternatives continues to increase throughout the 100 year period, proportional to the cumulative quantity of pellets or ethanol produced. A

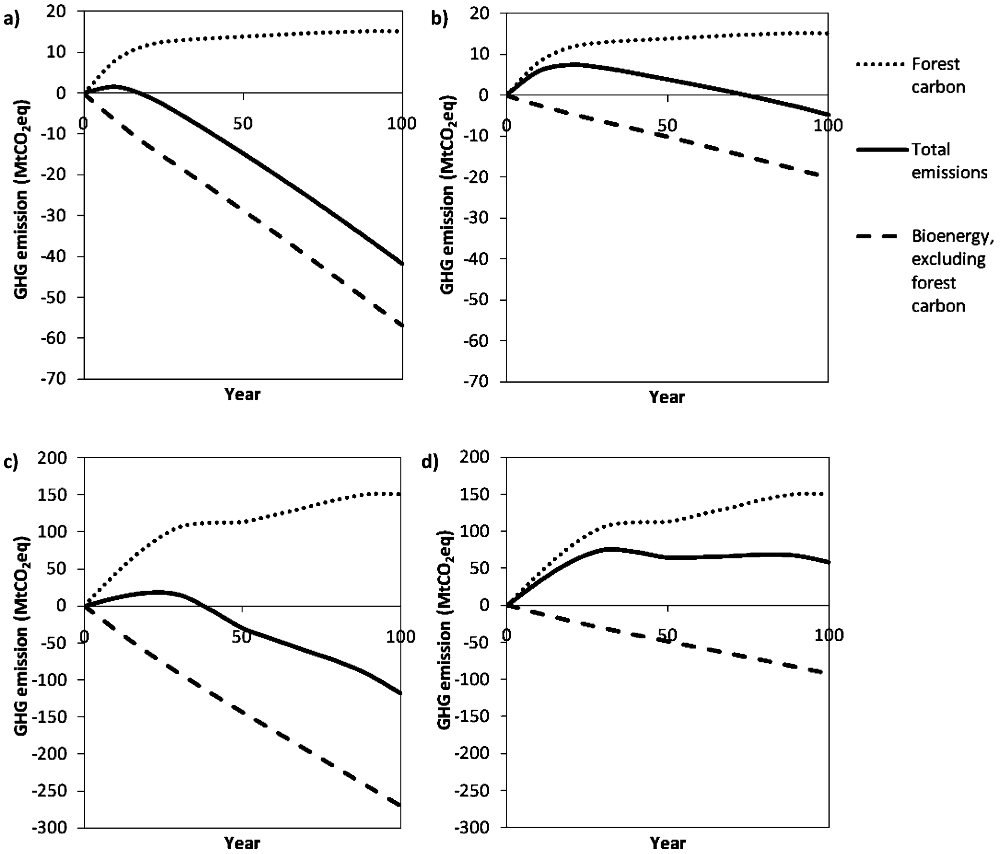

FIGURE 1. Cumulative GHG emissions from continuous biomass harvest for bioenergy production: (a) pellets produced from residues, displacing coal (20% cofiring), (b) ethanol produced from residues, displacing gasoline (E85 fuel), (c) pellets produced from standing trees, displacing coal (20% cofiring), and (d) ethanol produced from standing trees, displacing gasoline (E85 fuel). Positive values indicate an increase in GHG emissions to the atmosphere.

time delay therefore exists before bioenergy systems reach a "break-even" point where total emissions for the bioenergy and reference fossil pathways are equal. Only after the break-even point are net emissions reductions achieved.

Figure 1a and 1b shows the total emissions resulting from continuous use of residues for pellet and ethanol production, respectively, over a 100 year period. Excluding forest carbon, the emissions reduction associated with utilizing bioenergy in place of fossil alternatives increases steadily over time. The reduction of forest carbon stocks due to residue collection slows toward a steady state. Co-firing with pellets produced from residues reduces cumulative emissions relative to coal only after an initial period of increased emissions lasting 16 years. Forest carbon impacts of residue removal reduce the total emission mitigation at year 100 from 57 MtCO$_2$equiv (expected assuming immediate biomass carbon neutrality) to 42 MtCO$_2$equiv.

Compared to the electricity pathway results, utilization of residues for ethanol production is more greatly impacted by changes in forest carbon, due to the lower GHG intensity of the displaced fuel (gasoline compared to coal). An overall emission reduction occurs only after 74 years of continuous production of ethanol; total GHG reductions by year 100 are reduced by 76% from expected performance assuming immediate biomass carbon neutrality.

Due to the greater forest carbon impact of standing tree harvest compared to residue collection, bioenergy production from standing trees performs worse in terms of reducing emissions (Figure 1c and 1d). Pellet production from standing trees results in a greater initial emissions increase, reaching a break-even point only after 38 years of continuous production and use when displacing coal for electricity generation. The total emissions reductions from utilizing wood pellets from standing trees over a 100 year period, expected under the assumption of biomass carbon neutrality, is reduced by 56% when forest carbon impacts are considered.

As in the residue cases, for the standing tree cases forest carbon more significantly impacts total emissions of ethanol than those associated with pellets for electricity generation. Ethanol production from standing trees (Figure 1d) does not reduce emissions at any point within the 100 year period; instead, overall emissions to the atmosphere increase relative to the gasoline reference pathway. Disregarding biobased CO$_2$ emissions, as is common to most LCAs, would return an opposite, and erroneous, result. This contradiction, also identified elsewhere (*15*), illustrates the misleading consequence of assuming immediate biomass carbon neutrality when quantifying emissions of some bioenergy pathways.

Simply adding biobased CO$_2$ emissions associated with bioenergy production and use to the LCI totals presented in Table 1 would increase emissions associated with bioenergy. Pellet cofiring (at 20%) would result in (all in gCO$_2$equiv/kWh) 1039 (residue) and 1042 (standing tree) compared to 1001 for coal only. E85 would emit (all in gCO$_2$equiv/km) 711 (residue) and 718 (standing tree) compared to 288 for gasoline. This approach, however, would not accurately assess the impact of bioenergy production and use on the atmosphere. By only considering carbon in harvested biomass, near-term emissions would be underestimated (decomposition of uncollected biomass, for example, below ground biomass, is omitted). Mid- to long-term emissions would be overestimated as compensation for biobased CO$_2$ emissions within the forest (e.g., regrowth) is not considered.

Sensitivity Analysis. A sensitivity analysis is performed to assess the impact of key sources of uncertainty/variability in the LCI and forest carbon model parameters on the study results (see Supporting Information). The results are not sensitive to most parameters, and the general trends of the impacts of biomass harvest on carbon stocks and their contribution to overall emissions were not found to be impacted by uncertainty in the parameters. The pellet pathway results were found to be most sensitive to assumptions related to the quantity of biomass used for drying during pelletization (15% of input biomass in base case) (see Supporting Information Figure S-3). Reducing the consumption of biomass during the drying stage increases pellet output and fossil fuel displacement per unit of input biomass. Co-location of pelletization facilities with processes generating waste heat could reduce the drying energy requirement. If no input biomass is required for drying, there are larger emissions reductions associated with pellet use and the time before reaching break even with the fossil energy system is reduced from 16 to 11 years (residues) and from 38 to 29 years (standing trees). When forest carbon is excluded from the analysis, biomass utilization for drying energy has a minimal impact on LC emissions (*6*).

Study Implications. The simplified assumption of immediate biomass carbon neutrality has been commonly employed in bioenergy studies, owing in part to emissions from the energy and forest sectors being reported separately in national inventories (*17*). This study, however, shows that increasing biomass removals from the forest significantly reduces carbon stocks and delays and lessens the GHG mitigation potential of the bioenergy pathways studied. Ignoring the complex relationship between forest carbon stocks and biomass harvest by employing the carbon neutrality assumption overstates the GHG mitigation performance of forest bioenergy and fails to report delays in achieving overall emissions reductions.

Combining LCI analysis and forest carbon modeling as an analytical approach provides a more accurate representation of the role of forest bioenergy in GHG mitigation. When forest carbon dynamics are included in the case study, the use of forest-based bioenergy increases overall emissions for many years and, in the worst-performing scenario (standing tree harvest for ethanol production), does not yield any net climate mitigation benefit over the 100 year period. Carbon implications of bioenergy production are not limited to forests, and these results should not be taken to suggest that agricultural biomass is inherently preferable. Land use impacts associated with agriculture-sourced bioenergy can greatly increase LC emissions (*7*). Nonbioenergy systems can also impact carbon stocks (e.g., overburden removal in coal mining). While the contribution to total emissions may not be significant in all situations, a comprehensive evaluation of any fossil or renewable system should consider impacts of life cycle activities on terrestrial carbon stocks.

Do our results support continued reliance on fossil fuels for electricity generation and transportation? Fossil fuel use transfers carbon from the Earth's crust to the atmosphere; moving beyond reliance on these energy sources is imperative to address climate change and nonrenewable resource concerns. Bioenergy offers advantages over other renewable options that are limited by supply intermittency and/or high cost. However, effective deployment of bioenergy requires the thoughtful selection of appropriate pathways to achieve overall emissions reductions. Harvesting standing trees for structural wood products has been reported to reduce overall emissions: storing carbon in wood products and displacing GHG-intensive materials (steel, concrete) exceeds associated forest carbon impacts (*14*). In comparison, using standing trees for bioenergy immediately transfers carbon to the atmosphere and provides a relatively smaller GHG benefit from displacing coal or gasoline, increasing overall emissions for several decades. Identifying biomass supply scenarios that minimize forest carbon loss will improve the emission mitigation performance of forest bioenergy. Residues employed for bioenergy reduce emissions from coal after a much smaller delay than standing trees, while other forest biomass sources (e.g., processing residuals) could offer near-term emission reductions if used to replace GHG-intensive fossil fuels. Industrial ecology approaches (e.g., utilizing end-of-life wood products as a biomass source; integrating bioenergy production with other wood products to utilize waste heat for processing) could reduce forest carbon implications of bioenergy production and are deserving of further consideration.

Utilizing bioenergy to displace the most GHG-intensive fossil fuels minimizes initial emissions increases and reduces the time required before net GHG benefits are achieved. Ethanol production for gasoline displacement, under the modeled conditions, is not an effective use of forest biomass for GHG reductions. Displacing coal in electricity generation, in comparison, is superior in reducing emissions. However, this does not indicate that electricity applications are always preferable. The mitigation performance of biomass-derived electricity depends on the displaced generation source. Further, these results represent the expected near-term state of energy system technologies and do not consider changes in either the reference or the bioenergy pathways over the time frame studied. Performance improvements are inevitable with technological maturation and commercialization. Technological developments regarding thermal electricity generation (e.g., efficiency improvements; viable carbon capture and storage) would be applicable to both biomass and coal, while improvements in pellet production would not greatly influence total emissions. Emissions from producing ethanol, regarding both the ethanol production process and the appropriate reference pathway in the future given the limited petroleum supply and associated price volatility, is uncertain and in the future could prove a more effective means of emissions reductions than reported here. Ethanol can also play an important role in addressing economic and energy security concerns related to petroleum dependency.

Although the method demonstrated in this research is generalizable, site-specific characteristics of forests prevent the generalization of specific results from this study. Numerous factors would influence forest carbon dynamics and must be considered in specific analyses. Intensifying silvicultural practices (e.g., planting instead of natural regeneration, utilization of fast-growing species) could shorten, but not eliminate, the period of net emission increase found in our results. In some jurisdictions, residues are burned during site preparation for forest regrowth. Using such residues for bioenergy would not significantly impact forest carbon stocks.

While GHG mitigation is an important consideration of forest resource utilization, numerous other factors must be considered in the decision-making process. In particular, declines in Ontario's forest sector have negatively impacted communities that would welcome the investment and employment opportunities associated with bioenergy. Other environmental factors and technical constraints must be considered before implementing bioenergy production.

The potential of forest-based bioenergy to reduce emissions from fossil fuels must be balanced with forest carbon impacts of biomass procurement. This perspective is of particular importance as policies related to climate change mitigation, deployment of renewable energy, and the forest bioeconomy are developed and implemented. Considering bioenergy in isolation of its impact on forest carbon could inadvertently encourage the transfer of emissions from the energy sector to the forest sector rather than achieve real reductions. Accounting methods must be designed to measure the complete impact of mitigation options on the atmosphere. By considering the broader impacts of bioenergy production on the forest, particularly forest carbon pools, policy can lend support to effective uses of forest resources for climate change mitigation.

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Supporting Information Available

Additional detail on biomass sources, life cycle inventory of bioenergy systems, forest carbon analysis, and additional results and discussion. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Larson, E. D. A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. *Energy Sustainable Dev.* **2006**, *X* (2), 109−126; DOI:10.1016/S0973-0826(08)60536-0.

(2) Damen, K.; Faaij, A. A greenhouse gas balance of two existing international biomass import chains. *Mitigation Adapt. Strategies Global Change* **2006**, *11* (5−6), 1023−1050; DOI:10.1007/s11027-006-9032-y.

(3) Gustavsson, L.; Karlsson, A. A System Perspective on the Heating of Detached Houses. *Energy Policy* **2002**, *30*, 553−574; DOI:10.1016/S0301-4215(01)00128-8.

(4) GHGenius-a model for lifecycle assessment of transportation fuels, version 3.17; National Resources Canada: Ottawa, Ontario, Canada, 2010; available at http://www.ghgenius.ca/downloads.php.

(5) Cherubini, F.; Bird, N. D.; Cowie, A.; Jungmeier, G.; Schlamadinger, B.; Woess-Gallasch, S. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges, and recommendations. *Resour. Conserv. Recycl.* **2009**, *53*, 434−447; DOI:10.1016/j.resconrec.2009.03.013.

(6) Zhang, Y.; McKechnie, J.; CormierD. Lyng, R.; Mabee, W.; Ogino, A.; MacLean, H. L. Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada. *Environ. Sci. Technol.* **2010**, *44*, 538−544; DOI:10.1021/es902555a.

(7) Searchinger, T.; Heimlich, R.; HoughtonR. A. Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **2008**, *319*, 1238−1240; DOI:10.1126/science.1151861.

(8) Archambault, L.; Delisle, C.; Larocque, G. R. Forest regeneration 50 years following partial cutting in mixedwood ecosystems of southern Quebec, Canada. *Forest Ecol. Manag.* **2008**, *257* (2), 703−711; DOI:10.1016/j.foreco.2008.09.056.

(9) Schlamadinger, B.; Marland, G. The Role of Forest and Bioenergy Strategies in the Global Carbon Cycle. *Biomass Bioenergy* **1996**, *10*, 275−300; DOI:10.1016/0961-9534(95)00113-1.

(10) Hennigar, C. R.; MacLean, D. A.; Amos-Binks, L. J. A novel approach to optimize management strategies for carbon stored in both forests and wood products. *Forest Ecol. Manag.* **2008**, *256*, 786−797; DOI:10.1016/j.foreco.2008.05.037.

(11) *Biomass sustainability and carbon policy study*; Manomet Center for Conservation Sciences: Manomet, MA, 2010; available at http://manomet.org/sites/manomet.org/files/Manomet_Biomass_Report_Full_LoRez.pdf.

(12) Chen, J.; Colombo, S. J.; Ter-Mikaelian, M. T.; Heath, L. S. Future carbon storage in harvested wood products from Ontario's Crown forests. *Can. J. Forest Res.* **2008**, *38*, 1947−1958; DOI:10.1139/X08-046.

(13) Kurz, W. A.; Dymond, C. C.; White, T. M.; Stinson, G.; Shaw, C. H.; Rampley, G. J.; Smyth, C.; Simpson, B. N.; Neilson, E. T.; Trofymow, J. A.; Metsaranta, J.; Apps, M. J. CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecol. Model.* **2009**, *220*, 480−504; DOI:10.1016/j.ecolmodel.2008.10.018.

(14) Perez-Garcia, J.; Lippke, B.; Comnick, J.; Manriquez, C. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. *Wood Fibre Sci.* **2005**, *37*, 140–148.

(15) Searchinger, T. D.; Hamburg, S. P.; Melillo, J.; Chameides, W.; Havlik, P.; Kammen, D.; Likens, G. E.; Lubowski, R. N.; Obersteiner, M.; Oppenheimber, M.; Robertson, G. P.; Schlesinger, W. H.; Tilman, G. D. Fixing a critical climate accounting error. *Science* **2009**, *326*, 527528; DOI:10.1126/science.1178797.

(16) Baker, D. J.; Richards, G.; Grainger, A.; Gonzalez, P.; Brown, S.; DeFries, R.; Held, A.; Kellndorfer, J.; Ndunda, P.; Ojima, D.; Skrovseth, P.-E.; Souza, C.; Stolle, F. Achieving forest carbon information with higher certainty: A five-part plan. *Environ. Sci. Policy* **2010**, *13* (3), 249−260; DOI:10.1016/j.envsci.2010.03.004.

(17) Intergovernmental Panel on Climate Change (IPCC) In *Guidelines for National Greenhouse Gas Inventories*; Eggleston, S., Eds.; Institute for Global Environmental Strategies: Hayama, 2006.

(18) Abt, R. C.; Abt, K. L.; Cubbage, F. W.; Henderson, J. D. Effect of policy-based bioenergy demand on southern timber markets: A case study of North Carolina. *Biomass Bioenergy* **2010**, *34* (12), 1679−1686.

(19) Spatari, S.; Bagley, D. M.; MacLean, H. L. Life Cycle Evaluation of Emerging Lignocellulosic Ethanol Conversion Technologies. *Bioresour. Technol.* **2010**, *101*, 654−667; DOI:10.1016/j.biortech.2009.08.067.

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