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Quantifying the Life Cycle Greenhouse Gas Emissions of a Mechanized Shelterwood Harvest Producing Both Sawtimber and Woodchips

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Abstract: Forests are used to mitigate anthropogenic greenhouse gas (GHG) emissions through carbon offset programs, and forest management is generally accepted as "carbon neutral". However, forest harvesting operations depend heavily on fossil fuels, so it would be remiss to broadly paint all forms of management as carbon neutral without empirical verification of this claim. Biomass feedstock, as a means to supplant fossil fuel consumption, has received the bulk of investigative efforts, as the carbon benefit of biomass is one of the most contentious among wood products, because it does not create long-term carbon storage. A life cycle assessment (LCA) was conducted on a winter shelterwood harvest occurring in the Adirondacks of upstate New York. Primary data were collected daily throughout the operation and used to model the impact attributed to producing clean chips and logs for delivery to a pulp mill and sawmill, respectively. This harvest produced 4894 Mg of clean chips and 527 Mg of sawtimber. We calculated that 39.77 and 25.16 kg of carbon dioxide equivalent were emitted per Mg of clean chips and sawtimber, respectively, with a total observed flow of GHG into the atmosphere between 206 and 210 thousand kilograms. The results contribute to our understanding of the global warming potential of implementing a forest harvest to produce raw materials for medium- and long-term carbon storage products such as paper and dimensional hardwood lumber.

Keywords: forest management; carbon sequestration; silviculture; logging; biomass; life cycle assessment

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1. Introduction

Climate change necessitates an examination of environmental impacts from all human activities at the least, if not a moratorium of processes that are known to significantly contribute to climate change at most [1,2]. Forests are being used to offset anthropogenic greenhouse gasses (GHG), and forest management is considered a tool for mitigating climate change through carbon sequestering forests and the creation of carbon storing wood products [3–7]. However, the extraction and processing of wood-based products emits GHG due to infrastructure and machine dependence on fossil fuels. Although widely accepted to be "carbon neutral", there is ongoing debate regarding the magnitude of carbon flux from the atmosphere during forest harvesting and regeneration [8]. Uncertainty surrounding carbon accumulation rate as forests develop from stand initiation through old-age, and the carbon neutrality of old-growth forests themselves [9,10], further complicates the implications of management actions. Regardless of the carbon budget of resource extraction, forest management must continue providing societies' needs. The ambiguity regarding its role in climate change and the ceaseless demand for wood products, together, precipitates a need to understand the carbon implications of forest harvesting.

The emissions of air pollutants from timber harvesting have received international focus over the last several years in attempts to understand how processes to extract and manage natural resources contribute to climate change [11,12], among other environmental externalities [13–15]. Research comparing pollution from the use of different machines to complete similar tasks [16], as well as different operation techniques that influence the emissions of individual machines [12,17], have shown there are methods to reduce the emission of GHG and other pollutants such as nitrous oxides (NO_x) and particulate matter. However, many of these choices that loggers or land managers may want to implement are limited by the characteristics of their land and objectives. For instance, the transportation of timber products becomes less efficient as the terrain becomes more mountainous, and loggers can program their cut-to-length harvester heads to be more fuel efficient depending on the average stem size of trees [12,18]. The limiting factors identified in these publications are often out of the control of loggers, and may be beyond the control of land managers (e.g., their forests lay within a mountain range, or the optimal stand to harvest may have large average stem size). Moreover, to fully understand the potential impact of forest management on the climate a life cycle perspective is needed.

Life cycle assessment (LCA) is a standardized, multiphased, modeling process that can be applied to products or product systems to determine various categories of environmental impact and has been used extensively to analyze the forest products industry [8,19–23]. There are four iterative phases to be followed: goal and scope definition, inventory analysis, impact assessment, and interpretation. The goal and scope definition consists of selecting the system of interest and impact category and defining the system boundaries and functional unit. The inventory analysis step requires observing and quantifying the physical flows of inputs and outputs to the system. Impact assessment is when the environmental impact is characterized for the selected impact category. Interpretation is the final step, but should be occurring throughout the process, allowing the goal and scope to adjust to data availability and quality. Two approaches to LCA have developed: attributional and consequential. Attributional life cycle assessment focuses on observing the environmentally relevant physical flows in and out of the process in question, whereas consequential LCA seeks to understand how relevant flows would change due to management decisions or policies [24,25]. Despite the standardization of processes, proper application of either approach has been inconsistent, and universal methodologies for LCAs have not been developed [26–28]. Inappropriate application of either approach can exclude important activities from the system of interest and lead to misinterpretations of the results and poor decision-making [29–31]. Therefore, transparency produced from clearly stated goals and assumptions is paramount for correct interpretations of results.

LCA studies have examined sources of GHG involved with harvesting [32–34], although most of them focus on biomass feedstock harvesting for heat, power, or fuel sources [22,35–37], which do not provide long-term storage but have shown climate benefits as alternatives to fossil fuels. Substituting wood products for building materials such as concrete or metals resulted in considerable reductions in emissions [38]. Forest management and harvesting only contributed 3%–7% of the energy consumption for hardwood lumber produced in the northeast/north central regions, with the total impact for harvesting, transportation, and manufacturing at 502 kg carbon dioxide equivalent (CO_{2eq}) per cubic meter [39]. A comparative LCA of harvesting and transportation in Tennessee assesses the climate change impact of two harvesting configurations across three intensities of cutting—selective, shelterwood, and clearcutting. They concluded that between 22.9 and 49 kg CO_{2eq}/Mg are emitted during harvesting and transportation of roundwood, depending on transportation distances ranging from 50–250 km [21]. Manual harvesting systems, which utilize chain-saw felling and cable skidding, have a lower global warming potential (GWP) than mechanized harvesting because of disproportionately low inputs to the system which more than make up for reductions in productivity [21].

This study aims to quantify the GHG emissions during the extraction and processing of living trees into raw materials for lumber and paper manufacturing. While other studies of similar scope have examined biomass harvesting, the operation analyzed here produced clean chips and sawlogs that will be processed into paper and lumber that will eventually produce medium- and long-term carbon storage benefits. This process-based LCA estimates the cradle-to-gate life cycle GHG emissions associated with harvesting and transportation. Further processing of resources into finished products was outside the scope of this analysis. Subsequently, the results are more robust in their use as input data for analyses of life cycle stages further down the supply-chain and are applicable to a broader geographic range where the same products are extracted using similar harvest systems. Additionally, by excluding the processing stage and further downstream life cycle stages, these results are applicable for private mills that utilize the products seen here and seek to determine their own environmental impacts. The objectives for this case study are as follows: to quantify the GHG emissions associated with the harvesting of sawlogs and clean chips using primary and site-specific data, identify the sources of difference in the impact of both products, determine the sensitivity of impacts to changes in parameter values, and account for all forms of carbon within the system boundaries.

2. Materials and Methods

2.1. Study Area and Silvicultural Prescription

This harvesting operation case study was contracted by SUNY College of Environmental Science and Forestry as a Beech Bark Disease (BBD) remediation harvest at the Huntington Wildlife Forest (44°02′03″ N, 74°15′56″ W). Centrally located within the Adirondack Park in New York State (USA), the Huntington property encapsulates 6070 hectares and has been used for forest and wildlife research since its donation in 1932. The most recent commercial harvest of this site concluded in 1974 when the basal area was reduced from 28.65 to 10.3 m^2/ha. The forest has since regenerated naturally, but with an exceedingly high level of American beech growing to 11.4 m^2/ha, nearly a third of the overstory basal area, and almost nine thousand beech stems per hectare in the understory. Consisting of two cutting units (Supplementary Materials, Figure S1), totaling 49 hectares of maple–beech–birch forest, this harvest provided sawlogs and clean chips to a sawmill located 71 km away, and a paper mill 101 km away. The landing was located 13 km from a paved road which required extensive use of auxiliary equipment to prepare and maintain the forest road during the winter months, generating additional atmospheric impacts that are not produced in the same magnitude during roadside or summer harvests. Despite the history of harvesting in this stand, it has retained its land use, as forest. There is no history of land conversion.

The prescription was strongly influenced by the BBD complex; a disease that deteriorates wood and proliferates root sprouts, creating dense thickets that reduce the biodiversity and function of infected forests. Forest managers implemented a standard shelterwood harvest with the additional ramification to remove all beech stems greater than 1.5 m (5 ft) in height. The contracted logger utilized a fully mechanized harvest system consisting of two feller–bunchers, four skidders, two loaders, and one flail chipper. In bringing the average basal area from 38.75 m^2/ha (168.8 ft^2/ac) down to 11.8 m^2/ha (51.5 ft^2/ac), the harvest yielded 527 Mg of sawtimber and 4894 Mg of clean chips. In addition to the residual slash from processing sawlogs and preparing wood for the flail chipper, a considerable volume of biomass was left on site from the small beech stems mowed by the feller–bunchers. The stand is expected to regenerate as a northern hardwood stand with the hope that beech becomes a minor component of the species composition. The efficacy of this harvesting method as a BBD remediation strategy from an ecological standpoint will be the subject of future scientific inquiry.

2.2. Goal and Scope Definition

Our goal was to conduct an attributional LCA of a forest harvest using primary, site-specific data to determine the net carbon balance of using fossil fuel products to produce raw materials for forest products. The selected impact category was global warming potential. Attributional LCA studies seek to attribute all inputs and outputs to a functional unit using the current status of the product system and a given temporal window, as opposed to consequential LCA studies which seek to determine the consequences of changing characteristics or details of the product system for the purpose of influencing policy and decision-making [30,40,41]. The requisite use of a baseline land occupation for attributional LCA is a matter of some dispute [27,42,43], but we included a land-use baseline to analyze the results in the broader context of the carbon cycle.

The scope of this LCA was cradle-to-gate, including all processes involved from resource extraction up to the first gate when raw materials are delivered to their markets, but excluding the production, use, transportation, and end-of-life stages of the product life cycle. The exact activities included are represented by the System Diagram in Figure 1, but consist of all processes to cut, skid, and land trees, along with necessary auxiliary processes such as equipment manufacturing, equipment staging, road preparation, and maintenance. The dashed line represents the system boundaries, dotted lines represent subsystem boundaries which may be useful in interpreting the impact, and the arrows in and out of the system represent the physical flows that were observed. The selected functional unit, the unit to which the absolute emissions are scaled, is 1 Mg of green clean chips and 1 Mg of green sawtimber.

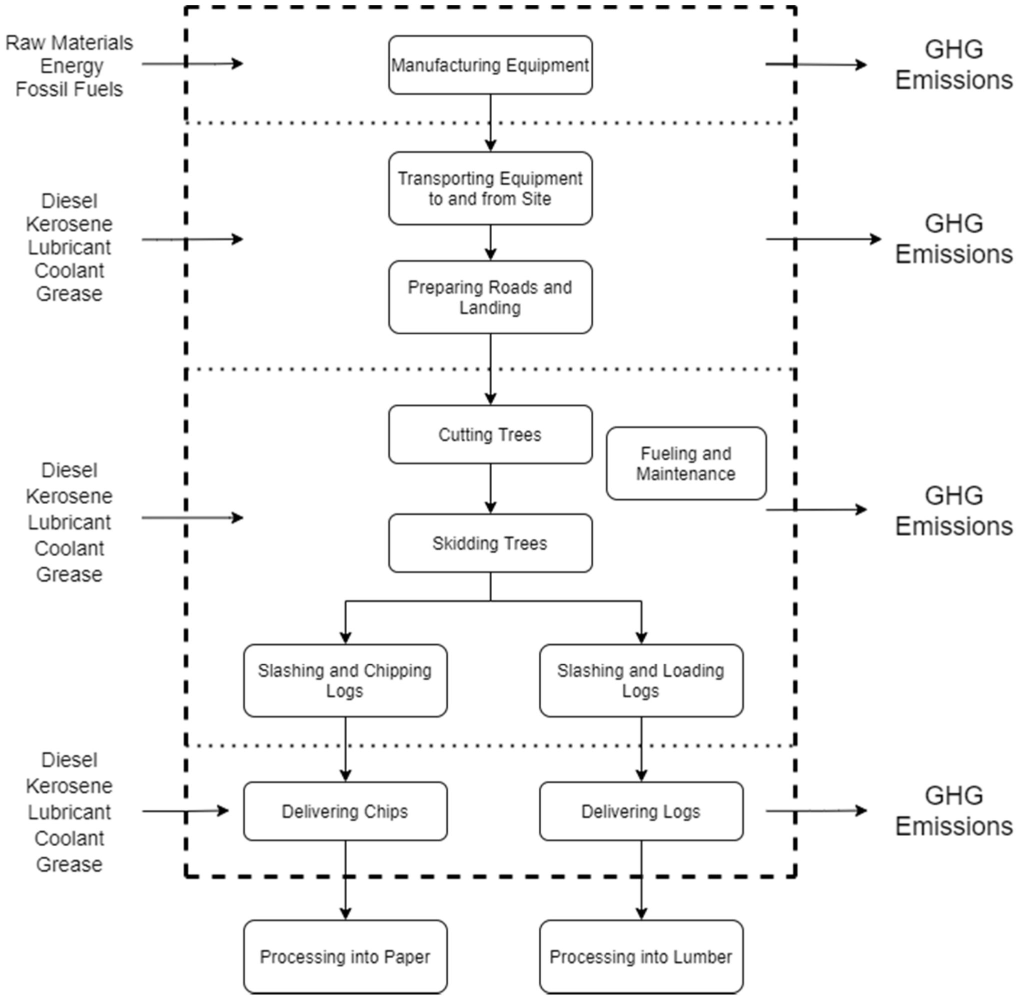

Figure 1. System Diagram depicting the system boundaries (dashed line) and subsystem boundaries (dotted lines) along with system processes or activities and observable flows in and out of the system boundary.

2.3. Inventory Analysis

The inventory data for this analysis consist of a combination of data collected from harvesting operation (e.g., production volume, diesel fuel consumption), existing LCA database (e.g., diesel fuel production and combustion), and the literature (e.g., equipment lifetime). Six interviews were conducted between February and March 2020 to collect information from the company owner and maintenance supervisor. Equipment operators provided daily journals to record their time and production. Operators also filled out a fuel sheet, and total fuel consumption from all equipment was provided by the owner at the close of harvest. In addition, the maintenance supervisor provided daily fuel use by machine which was required to delineate fuel consumption by process. The weight of lubricants, cost of grease, and type of coolant used by the machines was also collected from the owner. The maintenance supervisor provided the specifications for each piece of equipment regarding capacity of oil, hydraulic fluid, and coolant reservoirs, as well as each material's turnover rate. Finally, the owner provided the same breakdown of details for the trucks used for product transportation, and the maintenance and fuel truck. After the harvest concluded, a summary of all products delivered to the mills, or gate, was provided by the forest properties staff who facilitated contracting of the logger and collection of stumpage payments. The residual biomass was calculated using the Ecosystem Management Decision Support program (NED3) to compare the pre-harvest and post-harvest aboveground biomass and removing the mass of the products from the difference [44]. Data were collected in the summer of 2019, producing an estimate of standing biomass based on the sizes and number of stems per acre. In October of 2020, a post-harvest inventory was conducted that measured standing timber volume, and these data were subsequently entered into NED3, which allowed the program to calculate the total biomass removed during the harvest [44]. Our measurements for sawtimber and chip mass were subtracted from the NED3 output, yielding our calculation for residual harvested biomass. Tabular summaries of all fuel, lubricant, coolant, and grease consumption calculations are available (Table 1 and Supplementary Materials, Tables S1 and S2).

Table 1. Summary of machine characteristics used during the production of logs and clean wood chips from a shelterwood harvest.

Machine	Fuel (L/Hour)	Oil Capacity (L)	Hydraulic Fluid (L)	Coolant Reservoir (L)	Grease (Tubes/Day)
Feller–Buncher A	33.69	26.5	75.7	37.85	1
Feller–Buncher B	32.93	22.7	75.7	37.85	1
Skidder A	27.44	15.1	18.9	37.85	1
Skidder B	22.33	18.9	18.9	37.85	1
Skidder C	19.87	15.1	18.9	37.85	1
Skidder D	24.61	18.9	18.9	37.85	1
Loader A	23.66	18.9	75.7	37.85	1
Loader A	23.66	18.9	75.7	37.85	1
Bulldozer	20.28	24.6	56.8	37.85	1
Grader	17.10	24.6	143.8	45.42	1
Excavator	30.66	26.5	246.1	34.83	1
Utility Truck	13.52	6.6	-	4.73	0.14
Flail Chipper	66.24 (L/load)	68.1	193.1	49.21	1.2
Tractor-Trailer	1.74 (L/km)	37.9	-	45.42	0.14

To prevent the fuel from gelling in subzero temperatures, the logger used a 50% mixture of diesel and kerosene fuel. Using the productive hours recorded in the operators' journals, the average length of the workday was calculated for each machine. Then, using the average daily fuel use provided by the maintenance supervisor, the fuel was divided by the average workday to determine the average hourly consumption by machine. This value was then multiplied by the total productive hours for each machine, which corroborated the fuel use provided by the logging owner. Subsequently, the values were divided in half to provide the diesel volume and kerosene volume. Fuel consumed during equipment staging and transportation of products was calculated using the fuel efficiency of the trucks and the average transportation distance. It is important to note that while the wood products were delivered directly from the landing in the woods to their respective markets, fuel consumed by the trucks to drive from where they park at night to the landing, and from the market back to their parking space, must be accounted for as that fuel would not have been consumed if the harvest had not occurred. To calculate average delivery distance, the distances between where each truck parks at night and the landing, distances from the landing to the sawmill and paper mill, and distances from the mills to parking locations, were measured. The total mileage traveled by trucks was then reconstructed, separately for logs and chips, and then divided by fuel efficiency, then in half to calculated diesel and kerosene consumption.

Lubricants include engine oil and hydraulic fluid. For all machines, engine oil is replaced every 250 productive hours of use. Because there were no leaks or maintenance issues with oil during the job, the volume of oil consumed was calculated by dividing the volume of the oil reservoir for each machine by 250 and then multiplying by productive hours for the harvest. Mass in kilograms was then calculated by dividing the volume by the oil's density. The same process was followed for hydraulic oil, although the rate at which hydraulic oil is replaced varied by machine. The feller–bunchers, chipper, and loaders all experienced technical difficulties that required the replenishment of hydraulic fluid. Therefore, an exact volume of fluid used during the harvest was provided. For the skidders, the hydraulic fluid was replaced every 2500 h. The volume of the hydraulic fluid reservoir was divided by 2500, and then multiplied by the skidders' productive hours. For both oil and hydraulic fluid, the volumes were converted to mass in kilograms using their specific densities.

The process to measure coolant mirrored the lubricant process closely, except for the added complication that the petroleum derived product in antifreeze only comprises about 90% of its volume, and it is then diluted with water to become coolant. However, the same process was followed in that the specific coolant system reservoirs were recorded for each machine, and then divided in half to remove the volume that would be occupied by water. This volume was divided by the density of antifreeze to provide mass, but was then multiplied by the percent mass that is ethylene or diethylene glycol, the material generating the environmental impact. This mass of ethylene and diethylene glycol was then divided by the interval between coolant system changes (96 months) and multiplied by 1 month to provide the total mass of ethylene consumed during the harvest.

The characterization factor for grease is based on the amount of US dollars spent on it, meaning the volume of grease did not need to be measured, but the financial investment in grease did. The logger shared his purchasing price for a tube of grease (USD 2.25), and the maintenance supervisor explained that each machine should receive an entire tube of grease every day it is in operation. The chipper is the only exception in that it consumes 6 tubes of grease every 5 days. The total investment in grease was then calculated by multiplying its purchasing price by the number of machine-days for the harvest.

The harvest produced two distinct types of product, but were being produced simultaneously during many of the activities involved, and some activities did not produce any commercial products (e.g., mowing of beech whips by feller–bunchers), but were nonetheless necessary components of the system. This resulted in a multifunctional system. For processes that involved physical production, like felling and skidding, the consumption of materials that produce GHG is primarily a function of the time invested in the action, which is indirectly a function of the mass of the output. Because the biogenic carbon content of wood products depends on the mass of carbon stored in the wood [45], mass allocation was deemed most appropriate for this study.

For equipment staging, road preparation, felling, skidding, and maintenance, allocation was conducted by calculating the proportional mass of both products and then incorporating this proportion into the model to represent their environmental impact. This method is most appropriate for processes that produce both products simultaneously and have no further insight to separate the time attributed to either product. For the loaders, it is clear when they are slashing and loading sawlogs or preparing logs to be chipped. Given that all beech was chipped, their estimations for beech processed were completely attributed to the impact of clean chips. However, some of the chipped material included species other than beech. The approximate amount of time the loaders spent processing chips other than beech was calculated and it was added to their time spent on beech to provide the total proportion of time they spent on sawlogs and chips.

2.4. Impact Assessment

The impact assessment was conducted using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1) method, a tool developed by the EPA that provides characterization factors for a variety of substances across several impact categories [46]. Characterization factors quantify the environmental impact for various substances in terms of a common unit of equivalence. With the impact category of global warming potential, this equivalent substance is carbon dioxide and the unit is expressed as kg CO_{2eq}. Characterization factors convert the mass of these substances into the mass of carbon dioxide that would have an equivalent potential to warm the climate. The life cycle impacts of materials and chemicals used during all stages included in this analysis are calculated from the Ecoinvent 3 and USLCI databases using the EPA TRACI life cycle impact assessment method in SimaPro 8.2. The USLCI database provides up-to-date life cycle inventory data for commonly used products within the US, sourced by life cycle studies conducted within the U.S. [47]. The Ecoinvent database is international and provides around 18,000 datasets in a wide variety of study areas [48].

2.5. Interpretation

The interpretation stage of the LCA process includes interpreting the results of the study, but is intended to be practiced iteratively throughout the investigation. As the data collection for the life cycle inventory stage commences, there are opportunities for the data availability to prevent the successful analysis of the stated goal. Changes to the goal, scope, or inventory analysis can occur, but should be reflected in how the results are interpreted. During our assessment, it became clear that our ability to accurately measure the impact of equipment manufacturing was limited. We resolved to use the LCI values for equipment manufacturing from [23], because of similarities in equipment used in the harvest system, to minimize additional uncertainty to our results.

A sensitivity analysis was conducted to assess the response of the system when accounting for potential variation of the input parameters. The sensitivity models are simulated by holding all parameters at their baseline values and varying each parameter individually to determine its effect on total impact (Equations (1)–(3)). Individual variable input parameters were allowed to vary by up to ±25% from their baseline value. The list of the variable input parameters used is listed in Supplemental Materials (Table S2). The most influential variable input parameters were determined based on the relative percent range (Equation (4)) of the life cycle GHG emissions when parameters were varied by ±25% from their baseline value. Variable input parameter with the highest relative percent range was considered to be the most influential parameter.

$$x_{p,i} = \left(1 + \frac{p}{100}\right) \cdot \ x_{0,i} \tag{1}$$

$$Y_{baseline} = \sum_{j=1}^{n} Y_j(x_{0,1}, x_{0,2}, \ldots, x_{0,i}, \ldots, x_{0,m}) \tag{2}$$

$$Y_{p,i} = \sum_{j=1}^{n} Y_j(x_{0,1}, x_{0,2}, \ldots, x_{p,i}, \ldots, x_{0,m}) \tag{3}$$

$$r_i = \frac{|Y_{25,i} - Y_{-25,i}|}{Y_{baseline}} \cdot 100\% \tag{4}$$

where

$x_{0,i}$: the baseline value for the variable input parameter i;
p: the percentage change from the baseline;
Y_j : is the calculated impact for the process j;
$x_{p,i}$: is the new value of parameter i when it is varied by p percent from the baseline;
$Y_{p,i}$: the impact when varying parameter by p percent from its baseline value;

n: the number of processes or activities;
m: the number of variable input parameters;
r_i : relative percent range of the impact.

3. Results

We found the global warming potential of chips to be higher than the impact associated with logs. The impact of producing clean chips was 14.6 kg CO_{2eq}/Mg higher than sawlogs, with sawlogs generating 25.16 kg CO_{2eq}/Mg, and 39.77 kg CO_{2eq}/Mg of clean chips (Figure 2). The activities associated directly with the harvesting operation (i.e., skidding, felling, slashing, and chipping) contributed to 55 to 60% of the total emissions (Figure 3). The total emissions for the total harvest, including chips and sawlogs, equated to almost 210,000 kg CO_{2eq}, and over 4.9 million kg CO_{2eq} were stored in the raw materials sold to mills. The forest inventory results showed that there was a difference in pre- and post-harvest aboveground biomass of about 170.15 Mg/hectare. Removing the mass of the commercial products provided a final estimate of 58.68 Mg/hectare of residual harvesting slash, or a total of 2854 Mg of biomass.

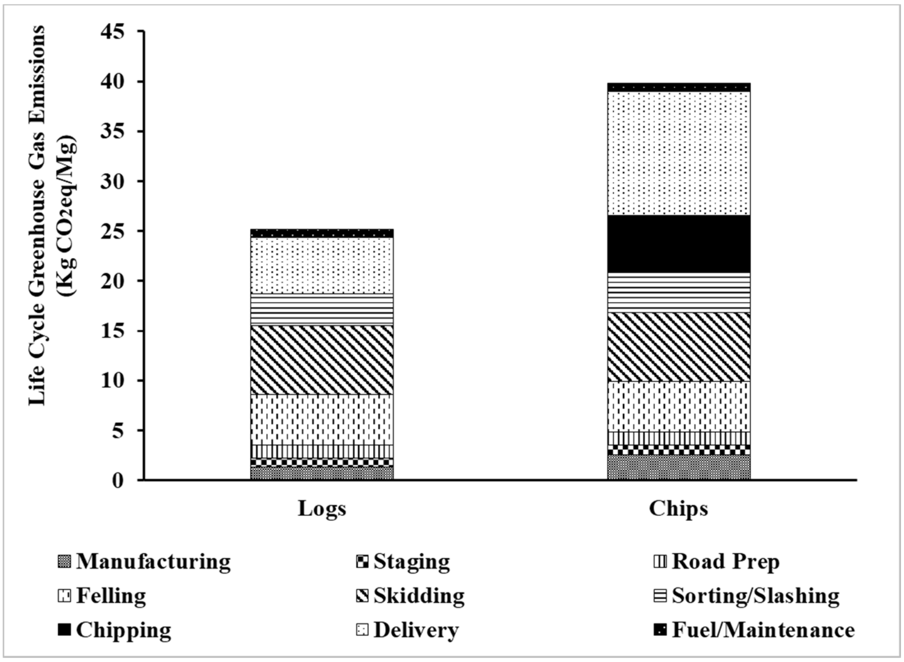

Figure 2. Life cycle GHG emissions of the production of logs and wood chips from a shelterwood harvest.

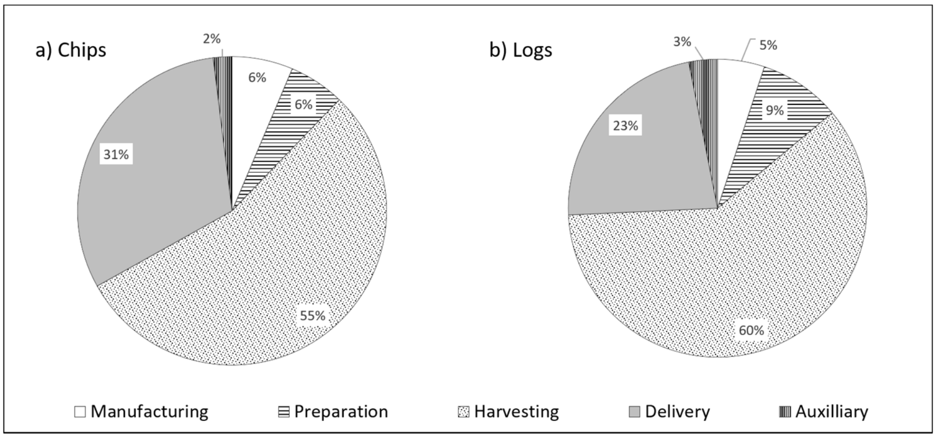

Figure 3. Contribution of different stages to the life cycle greenhouse gas (GHG) emissions for (**a**) wood chips production and (**b**) logs production.

The difference between the impact of chips and logs is mainly due to the additional machine and processing involved with producing clean chips and farther distance to the paper mill than the sawmill. The processes of equipment manufacturing and staging were marginally higher for chips because of accounting for an additional machine. Moreover, chipping, a process that is not involved with sawtimber production, alone generated 5.7 kg CO_{2eq}/Mg. Not only was the paper mill 30 km farther from the landing than the sawmill, but the weight of a load of chips averaged 1 Mg less than a load of sawtimber, requiring additional trips to deliver chips that would otherwise not have been necessary if the weight of loads were equivalent for both products. Furthermore, the largest sources of GHGs were skidding for sawtimber and product delivery for clean chips. However, the per unit emissions from road preparation, skidding, maintenance, and felling were equivalent for both products.

To have a more direct comparison between clean chips and logs, we recalculated the impact if the transportation distance to their respective markets were equivalent. When both mills are equidistant from the landing (71 km), the emissions from harvesting and delivery of clean chips were reduced to 34.4 kg CO_{2eq}/Mg (Supplementary Materials, Figure S2). Therefore, harvesting and delivering wood chips result in higher GHG emissions per unit of mass than sawtimber when the impacts of the shared processes were allocated by mass. It should be noted that a different allocation approach (e.g., economic value) may lead to different conclusion. However, the ISO standard recommends use of the economic allocation approach when it is not possible to use physical relationship (e.g., mass, volume, or energy).

The sensitivity analysis demonstrated that the amounts of diesel and kerosene consumed by the equipment are the most influential parameters affecting the life cycle GHG emissions of the harvest system (Figure 4, see Tables S3 and S4 in the Supplemental Materials for the complete list of parameters). This may be unsurprising because both forest harvesting and delivery of wood products strongly depend on the consumption of fuels, representing 86% and 83% of the total impacts associated with wood chips and logs, respectively (Figure 3). For logs, diesel fuel consumed during equipment staging lead to a change of ±0.43% of our baseline estimate for a 25% change in parameter value. For chips, fuel consumed during sorting and slashing changed the baseline estimate by ±1.2% for a 25% change in parameter. All other materials consumed for these activities, and all parameters of the activities not presented, influence the total impact for either product by less than these respective values. The machine life hours were the only parameters to have an inverse relationship with impact, although the system was still less sensitive to changes in their values than for changes in staging diesel for logs or sorting and slashing diesel for chips.

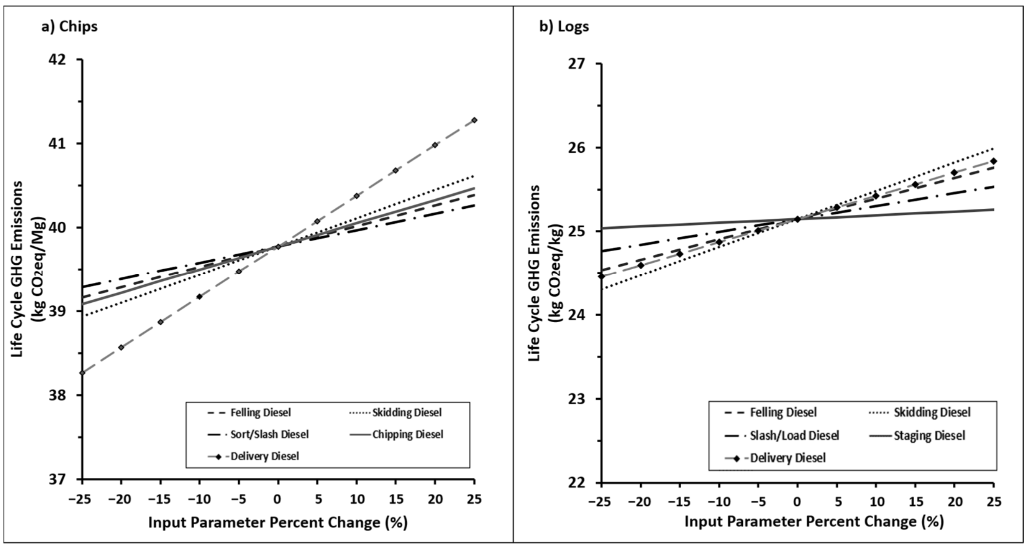

Figure 4. Sensitivity results of the top five most influential variable input parameters on the life cycle GHG emissions of (**a**) chips and (**b**) logs.

4. Discussion

The results of our study indicate that approximately 65 kg CO_{2eq}/Mg in emissions were generated during a mechanized shelterwood harvest that yielded 527 tonnes of sawtimber (99.5 MBF) and 4893.9 tonnes of clean chips. Roughly 40 kg CO_{2eq}/Mg were associated with harvesting operations while the balance was dedicated to transporting the products to destination mills. Our results for harvesting emissions are nearly twice of those reported by [21], although the harvest systems and silvicultural circumstances were considerably different between the two studies. Our results do support their findings that truck payload, fuel economy, and market distance are among the most influential factors to the total impact of resource extraction. The emissions for a given one-way transportation distance were nearly identical, although these do not fit the linear trend they depicted between transportation distance and GHG emissions. Their results showed 0.11 kg CO_{2eq} were emitted per kilometer of transportation, although no details were included regarding the mass of product being transported, whereas we found 0.08 kg CO_{2eq} were emitted per kilometer.

An LCA of biomass feedstocks in the northeast region found the impact of harvesting clean chips to be 27.89 kg CO_{2eq}/Mg when using a mass allocation [23], which is only 0.5 kg/Mg higher than our results for the unit impact of clean chips using mass allocation and directly within the probability distribution for this value. The scope for both studies is nearly identical: logging equipment manufacture, operation, and maintenance, staging of equipment, harvesting operations, and processing of material on site and loading into trucks are included in both studies. The only difference is that this harvest did not require site preparation and best management practices were included within the other system processes in this case study, whereas BMPs were given their own process in the biomass feedstock LCA. The differences between individual system process impacts were markedly higher than the variation between entire systems when comparing our findings to that of [23]. The processes of equipment manufacturing, equipment staging, and chipping were on average 2 kg CO_{2eq}/Mg lower for our system compared to their results. Unfortunately, there is little information regarding the details of each harvest system analyzed within their study. A discrepancy this small, as our sensitivity analysis illustrates, could come from an explanation as simple as the productivity or efficiency of the comparative harvesting operations. The harvest for this study also occurred during the winter, which was not clarified in the other study. The global warming potential of kerosene combustion is 0.139 kg CO_{2eq}/L higher than for combusting diesel fuel, which would also partially explain why the emissions calculated in this case study are slightly higher if the other harvests did not occur during the winter, requiring kerosene.

The difference between the impact of clean chips and sawtimber derives principally from the additional processes of debarking and chipping that are not necessary for sawtimber. Conceptually, this finding seems intuitive in that there is not only an additional machine required to produce clean chips, but the raw material itself must undergo a drastic physical transformation in which stems, weighing upwards of a metric ton, are turned into small pieces that, individually, weigh a few ounces. However, the placement of system boundaries can significantly influence analysis by excluding stages of the life cycle, which can misrepresent the true impacts of a product [31]. It should be made clear that these results only represent impacts from before the processing stage of the commodities' life cycles. While our system boundary captures the entirety of the extraction process, it excludes further processing of clean chips and any processing of sawlogs. Without further investigation, we cannot confirm whether the debarking and chipping process depicted in this study produces greater GHG emissions than the processing sawlogs undergo to produce lumber. The more commanding differences in their climate impact will be the resulting biogenic carbon being stored in lumber for 50–100 years, whereas the paper will only provide benefits for 3–5 years. Irrespective of the comparative benefits of one product over the other, this judgment is not the purpose of this investigation, nor would it be an accurate way to interpret the results of an attributional LCA.

The attributed impact of sawlogs or chips is incomplete without a comparison to the reference land occupation of the spatial boundary. With land management activities such as forest harvesting, selection of the proper reference land occupation changes the impact of the system [27,42,43,49]. A literature review of 700 LCA publications was performed in [27], which found that there were generally four baseline references for land use: zero baseline, business as usual, natural, or quasi-natural steady state, and natural regeneration. The results for using natural regeneration can be difficult to accurately determine, but this reference land use allows for attributing the foregone carbon sequestration to the product system. For lands that are managed to provide forest products, yet remain as timberland in perpetuity, natural regeneration most accurately describes the reference land use. Quantification of the impact from foregone sequestration would require long-term measurements of sequestration rate of the site. Our LCA and results are accurate for a temporal window of the 31 days the harvest was occurring. Utilizing a conceptual model of the forest system (Figure 5) allows us to speculate on the possible impacts of the foregone carbon sequestration for a temporal window of an entire rotation or cutting cycle of the forest, or an indefinite timeframe. In this discussion, the temporal boundary will be from the first day of harvesting until 2150, with the assumption that no further harvesting is to occur.

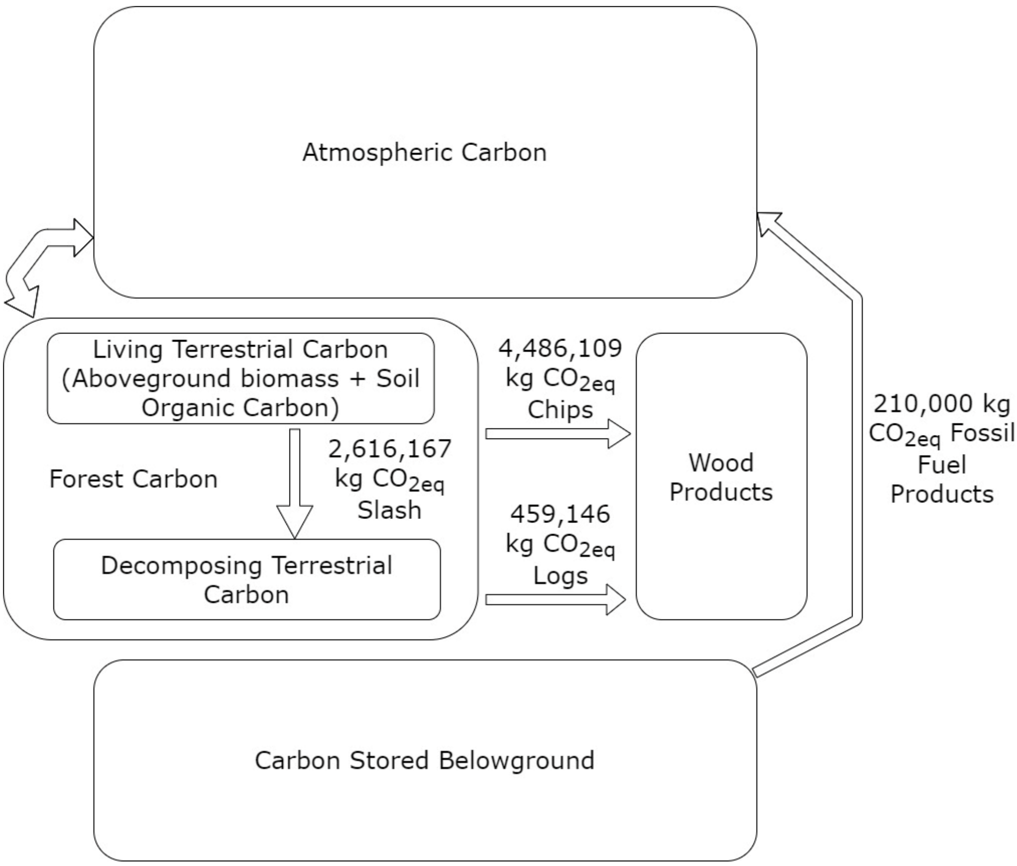

Figure 5. Carbon model depicting major carbon sinks and the observed physical flows produced from harvesting.

The forest was most recently harvested in 1974 with a shelterwood cut that left an on-site overstory with a basal area of 16.3 m^2/ha. Although a second harvest usually occurs after a shelterwood to remove the overstory, allowing the advance regeneration and understory to be released from competition, there is no record of a second cut. The understory proceeded to regenerate to our pre-harvest levels. By now, the overstory is likely all mature trees which are growing at a considerably slower rate than an adolescent cohort of the same species. The overstory would continue growing relatively slowly until trees begin to senesce, and understory trees grow to take their place. We predict that without further human intervention, this stand would reach a climax steady state by the year 2150. When forests reach advanced ages, the rate of ecosystem respiration, or release of carbon, begins to approach the rate of gross primary production, or the rate of carbon uptake driven by photosynthesis [10,50,51]. The theory that old-age forests become atmospherically carbon neutral, meaning their rates of carbon uptake and release are equivalent, was originally posited by [52]. While neither confirm that respiration and photosynthesis are a net wash in old temperate forest, previous research has demonstrated that these forests accrue carbon at a higher rate for ages 10–100 compared to after 100 years of age, void of any major disturbances [10,51]. This means the forest during the next 130 years would continue to accumulate carbon at a progressively slower rate, accounting for growth and decay of aboveground and belowground carbon. Soil carbon pools increase continually with forest age, at least up to 200 years, the upward limit of forest ages in the study [51]. Residence times for coarse woody debris of this species mix and climate ranges from 71 to 84 years, with the half-life of 10 or 11 years, meaning about half of the carbon in the residual biomass will be released over the next decade [53]. If dead wood decomposes nearly entirely within a century, yet the soil carbon content continues to increase throughout a 200-year span, then it stands to reason that not all the carbon in the harvesting slash will enter the atmosphere and contribute to radiative forcing. The exact amount that will leave the forest system through respiration by 2150 will ultimately depend on the completeness of decomposition and the proportion that becomes living biomass in fungal tissue or undergoes mineralization in the soil. A carbon deficit between respiration and photosynthesis is an empirically well-established phenomenon for stands developing from initiation following natural disturbance [10,50]. However, this harvest also left standing trees on site, and advance regeneration is expected within the next decade. By comparison to a natural stand replacing disturbance (i.e., fire in which the living biomass is converted mainly to atmospheric carbon, or major windthrow where all the living biomass becomes decomposing biomass on site), this disturbance left living biomass that will continue to grow, immediately tempering the pulse of respiratory carbon into the atmosphere. Additionally, the living biomass was removed from the site in the form of biogenic carbon [45], both long- and short-term. The clean chips will become paper, which is considered to provide carbon storage benefits for 3–5 years while the lumber carbon benefits range from 50 to 100 years.

Considering how the forest would develop if no harvesting had occurred, our model would look similar, but without the reported physical flows of carbon. The sequestration rate would likely be relatively low, given the advanced age of the stand. Although it would admittedly be a much lower amount, there would still be a flux of living forest carbon into the dead and decomposing forest carbon over time. In the year 2150, assuming an absence of disturbance, a small movement of carbon from the atmosphere to the forest would be the only net flow in between the belowground, aboveground, and atmospheric carbon pools. Re-examining the model with the forest harvesting flows of carbon, there is a movement of below ground to atmospheric carbon, and a significant transformation of aboveground carbon from one form to another. Over the next 130 years, the sequestration rate will be, on average, much higher than the unharvested alternative. The determination of the impact of these products on this timescale would therefore depend on the change in sequestration rate from an unharvested alternative, but if the biogenic carbon in the sawlogs continues to store carbon at the end of this period, it would mean that forest harvesting for long-term wood storage products could effectively siphon the carbon dumped into the atmosphere from fossil fuel consumption out of the atmosphere, assuming that the forest retains living biomass on site over the entire timeframe. Empirical evidence to support this claim would be the measurements of the annual rate of carbon sequestration for a mature and regenerating forest over the course of 130 years, and subsequently taking the difference of the Reimann sums of their growth functions to calculate the net loss or gain of carbon storage.

5. Conclusions

Forest management is a critical tool for mitigating climate change through carbon sequestration in the forest and the creation of carbon storing wood-based products. However, sustainable forest management requires periodic harvesting, processing, degradation of organic matter, and transportation of forest products, which results in GHG emissions. Although widely accepted to be "carbon neutral", it is imperative that we improve our understanding of the carbon implications of harvesting and transporting wood products to destination processing mills. This process-based LCA case study provides a high-resolution estimate of GHG emissions from the point of harvesting to the mill gate. The emissions for the total harvest equated to almost 210,000 kg CO_{2eq} that resulted in 25.16 kg CO_{2eq}/Mg for sawlogs and 39.77 kg CO_{2eq}/Mg for clean chips. An estimated 4.9 million kg CO_{2eq} were stored in the raw materials sold to mills. This represents a ratio of carbon emissions to stored carbon in delivered wood products of 4.3%. The significance of this ratio will prove more meaningful as future LCA research examines carbon emissions beyond the mill gate when logs and clean chips are manufactured into final products.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f13010070/s1, Figure S1: Harvesting blocks T1 and T3 with digitized skid trails and landing, Figure S2: Life cycle greenhouse gas emissions of sawlogs and clean chips under the hypothetical scenario that both the paper mill and the sawmill are located 71 km away from the landing, Table S1: Details of fuel, lubricant, and coolant consumption for all the machines, Table S2: Summaries of material produced and all fuel, lubricant, coolant, grease, and equipment used during a mechanized shelterwood harvest producing both sawtimber and woodchips, Table S3: Sensitivity analysis results of the life cycle greenhouse gas emissions of wood chips when varying the input parameters by a given percentage from their baseline values, Table S4: Sensitivity analysis results of the life cycle greenhouse gas emissions of logs when varying the input parameters by a given percentage from their baseline values.

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