Development of economic and environmental metrics for forest-based biomass harvesting

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Abstract. An assessment of the economic, energy consumption, and greenhouse gas (GHG) emission dimensions of forest-based biomass harvest stage in the state of Michigan, U.S. through gathering data from literature, database, and other relevant sources, was performed. The assessment differentiates harvesting systems (cut-to-length harvesting, whole tree harvesting, and motor-manual harvesting), harvest types (30%, 70%, and 100% cut) and forest types (hardwoods, softwoods, mixed hardwood/softwood, and softwood plantations) that characterize Michigan’s logging industry. Machine rate methods were employed to determine unit harvesting cost. A life cycle inventory was applied to calculating energy demand and GHG emissions of different harvesting scenarios, considering energy and material inputs (diesel, machinery, etc.) and outputs (emissions) for each process (cutting, forwarding/skidding, etc.). A sensitivity analysis was performed to evaluate input variables for the harvesting operation in order to determine their relative importance. The results indicated that productivity had the largest impact on harvesting cost, followed by machinery purchase price, yearly scheduled hours, and expected utilization. Productivity and fuel use, as well as fuel factors, are the most influential environmental impacts of harvesting operations.

1. Introduction

Increasing concerns associated with global warming have caused regulatory agencies and nongovernmental organizations (NGOs) to require a sharp reduction in greenhouse gas (GHG) emissions from the transportation sector, U.S. [1]. Depletion of fossil fuels supports the need for alternative, renewable energy resources for transportation [1]. Ethanol produced from renewable feedstocks (e.g., woody biomass, agricultural residues, energy crops) could serve as a substitute for gasoline and thereby help reduce GHG emissions and contribute to achieving environmental goals.

To ensure economically feasible and environmentally beneficial biofuel production, decreasing energy consumption and GHG emissions from cradle to grave life cycle of the biofuel is necessary [2]. The harvesting operations of biomass represent the largest component of cost associated with biomass energy production and generation [2]. The economic and environmental assessment of the supply chain focused on forest-based biomass in Michigan. Forest-based biomass is a major feedstock source of woody biomass from forestlands in the U.S. [2]. The statewide timberland acreage data from U.S. Forest Service indicates that it is the seventh largest in the U.S. [2]. And the current

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annual growth exceeds annual mortality and removals in most types of forest [2-3]. In addition, decline in other traditional roundwood industries (pulp and lumber) in recent years have opened up new prospects for the sustainable use of forest resources [4].

The goal of this study is to develop economic and environmental impact performance metrics for forest-based biomass harvesting cost, energy demand and GHG emissions within the state of Michigan. The three factors are considered as measures of economic growth, energy security, and environmental protection, respectively [1]. To this end, the following were conducted: (1) a harvesting cost analysis using the machine rate costing method, and (2) a life-cycle assessment (LCA) procedure for energy demand and GHG emissions estimation. Both methods were used to evaluate a series of forest biomass harvesting scenarios differentiating harvesting systems, harvest types, and forest types that characterize Michigan’s logging industry.

A forest harvesting system is defined as the method of organizing forestry equipment and duties among loggers to harvest the particular forest in the most effective way possible [5]. The three main harvesting systems of forest in the Michigan’s logging industry are [6-7]: (1) cut-to-length (CTL) harvesting with harvester/forwarder; (2) whole tree harvesting (WTH) with feller-buncher/grapple skidder/slasher; and (3) motor-manual harvesting (MMH) with chainsaws/cable skidder, as illustrated in Figure 1. After being felled with a feller in the cut-to-length harvesting solution, timber is delimbed and bucked into, for example, pulpwood logs for biofuels, at a stump [8]. Logs are then transported via a forwarder to the roadside [9]. With the WTH method, trees are felled and transported to the roadside with branches and the top intact. The whole trees are processed at the roadside into pulpwood logs [9]. After trees are felled and bucked with a chainsaw in a MMH system, they are skidded to roadside by a ground-based cable skidder [5].

The three dominant harvest types evaluated were (1) removal of all merchantable trees, (2) a 70% removal of all merchantable trees, and (3) a 30% removal of all merchantable trees [6-7]. Forest resources are differentiated by natural hardwoods, natural softwoods, mixed hard and softwood, and softwood plantations [6-7].

This study is the first to run an explicit assessment of the three indicators (cost, energy and emissions) for Michigan’s harvesting activities differentiating harvesting systems, harvest types, and forest types. Previous LCAs of biofuel produced from various biomass feedstocks focused on environmental performance of producing and supplying feedstocks [7, 10-14], without paying much attention on economic viability. Moreover, the evaluation of harvesting/forwarding activities was mostly based on the assumption of employing cut-to-length harvester/forwarder only [12] or whole tree harvesting system only [13]. Other studies did not differentiate harvest type (assuming 100%
clear-cutting) [12] or forest type for environmental impact assessment [14]. This research expands on the scope of prior work and adds to the existing body of knowledge in this research area.

The rest of this paper is structured as follows. Section 2 describes the research methods along with the goals and the scope definition, functional unit, and life cycle input data. The results are presented and discussed in Section 3. Sensitive analysis on key input variables is performed and presented in Section 4. Section 5 concludes the discussions to include research findings and major contribution.

2. Material and methods

2.1. LCA method

2.1.1. Goal and scope.

LCA is an effective tool to identify environmental implications but does not account for the economic implications [1]. The primary goal of the LCA is to evaluate energy consumption and GHG emissions from forest harvesting operations in Michigan, U.S. System boundary defines the scope for LCA and is illustrated in Figure 2. Harvesting activities include cutting standing trees from the stump, processing them into typical log length (e.g., 2.54 m), and then transporting processed logs to forest landings [14] (Figure 2). Activities from “upstream” inputs of the biomass feedstock production are excluded from this study. These “upstream” activities may include forestation and landscape carbon stock changes due to direct and indirect land use change [14]. We also excluded inputs for “downstream” activities of producing, distributing and end use of biofuels.

2.1.2. Functional unit.

One green tonne of pulpwood is the functional unit which includes the harvesting and collection using forestry machinery commonly found in Michigan. For the purpose of this study, a green tonne is at 50% moisture content wet basis [14]. Since no byproducts were considered, the environmental impacts were assigned to bioethanol as the primary product.

2.1.3. Life cycle input data.

Environmental impacts of producing energy and material inputs as well as the direct utilization of them in the forest harvesting activities [15] were included as part of the LCA using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model [16], peer-reviewed scientific articles, reports, or other sources. These material and energy inputs included fossil fuels, major machinery used to harvest wood (e.g. harvesters, forwarders), and lubricants and other inputs during machine fabrication, maintenance and large process equipment replacing [14]. The global warming potential (GWP) was established to measure a particular chemical’s propensity to cause global climate change represented by carbon dioxide equivalents (CO₂eq) over different time horizons [17]. For this application, emissions of greenhouse gases, such as CO₂, N₂O, CH₄, etc, were normalized using the IPCC GWP 100-year average and then aggregated for the overall impact estimation of a process or product.
2.2. Harvesting cost analysis method

Two key methods to establish harvesting costs are the machine rate and cash flow methods [18-19]. The cash flow method applies past data of loggers to develop a harvesting cost ($/tonne), by adding business related costs and for the tonnes of timber delivered for the last year. The actual average harvesting cost for the prior year is calculated by dividing the harvesting cost ($/tonne) by the tonnes of timber delivered [19]. It should be noted that this method performs poorly on distributing larger costs associated with, e.g., equipment purchases and capital equipment maintenance except that all equipment is leased [19]. The machine rate method combines hourly system costs and productivity to predict a harvest cost [19], which is useful when predicting the approximate hourly costs of a machine and for cost comparison between two machines [18]. It has been identified as the most common approach of estimating the cost of individual machines and forest harvesting operations [20-21], and thus was employed for this study.

The machine rate method divides hourly system cost by estimated productivity to derive harvesting cost [18]. Productivities were collected for the three harvest types in Michigan as stated above. The hourly system cost was calculated by adding up machine cost per hour for each piece of equipment in a harvesting system [19]. Hourly machine cost was calculated using the machine rate model of Machine Costing Spreadsheet from Virginia Polytechnic Institute [19]. The spreadsheet allows users to enter basic machine costing values to calculate fixed, operating, and labor costs for the machine. Basic machine costing values were collected from different sources like manufactures, peer-reviewed research papers, reports, and Bureau of Labor Statistics [22]. In particular, purchase price was collected by contacting forestry equipment manufacturers and local dealers, such as Forestry Equipment Sales [23], and Machinery Trader [24]. Different equipment models from brands like Caterpillar, John Deere, and Timberjack were considered. The purchase prices presented in Table 1 are averaged values without indicating specific brands or models. As expected, the purchase price of the CTL forest machines is higher than that of MMH machines. This may be because CTL machinery is technically more advanced. The other main fuel consumption is lower with CTL harvesting machines than with WTH machines, which may be a result of the CTL machines lighter weight. These conclusions are consistent with those drawn by Ponsse specialises in harvesting solutions for CTL logging [25]. Fuel consumption with chainsaw systems is significantly lower compared to the more mechanized system.

| Harvesting System | Equipment          | Purchase Price ($) | Fuel use \( (l/\text{hr}) \) |
|-------------------|--------------------|--------------------|-------------------------------|
| CTL harvesting    | CTL harvester      | 400,000            | 18.55                         |
|                   | Forwarder          | 350,000            | 12.11                         |
|                   | Feller-buncher     | 200,000            | 23.85                         |
| WTH system        | Grapple skidder    | 260,000            | 19.31                         |
|                   | Slasher            | 150,000            | 14.76                         |
| MMH system        | Chainsaw           | 1,500              | 4.16                          |
|                   | Cable skidder      | 250,000            | 9.08                          |

Source: \(^{a}\) Collected from Abbas et al. [6]

The remaining basic machine costing values were assumed as follows:
- Depreciation period was assumed to be 20 years [26-27] for equipment and 5 years for chainsaws. The straight line method was employed for calculating depreciation.
- Salvage value was assumed as 10% of the initial investment [26].
- The full time utilization rate of equipment was assumed to be 2,000 hours per year. The calculation was based on 8 hours/day for a 5 day per week. For 52 weeks/year and a two week breakup for vacation, it would be 8 hours x 5 days x 50 weeks = 2,000 hours/year.
- An interest rate of 8% and an insurance/taxes rate of 7% were applied [28].
Maintenance and repair costs were assumed as 50% of depreciation [29].
Machine utilization rate was assumed as 65% [29], and
A labor rate of $16.17 per hour (2012 Median pay, including fringe benefits) [22] was assumed for logging workers.

3. Results and discussion

3.1. Harvesting costs
The resultant cost estimate (Table 2.) is per Scheduled Machine Hour (SMH), that is, for every working hour of the machine is scheduled plus downtime [19]. Based on the machine rates in Table 2, the system cost for the three harvesting systems of CTL, WTH, and MMH are $114.33 SMH, $138.01 SMH, and $63.07 SMH, respectively.

| Equipment       | Fixed operating cost | Running cost | Labor cost | Hourly machine cost |
|-----------------|----------------------|--------------|------------|---------------------|
| CTL harvester   | 26.18                | 18.85        | 16.17      | 61.20               |
| Forwarder       | 22.90                | 14.06        | 16.17      | 53.13               |
| Feller-buncher  | 13.09                | 20.96        | 16.17      | 50.22               |
| Grapple skidder | 17.01                | 18.33        | 16.17      | 51.51               |
| Slasher         | 9.82                 | 10.29        | 16.17      | 36.28               |
| Chainsaw        | 0.21                 | 2.98         | 16.17      | 19.26               |
| Cable skidder   | 16.36                | 11.29        | 16.17      | 43.81               |

Average harvesting cost ($/tonne) was calculated for each harvesting system (CTL, WTH, or MMH) in each harvest type. The results are illustrated in Figure 3. As expected, average harvesting cost for the MMH system is higher than the more mechanized systems (CTL and WTH) across most forest and harvest types. For both fully-mechanized systems of CTL and WTH, average harvesting cost decreased as removal intensity increased from 30% to 100%, with WTH slightly higher than CTL in most cases except for shelterwood cutting on natural hardwoods and clearcutting operations on natural hardwoods and mixed hardwood/softwood. This may be because more machines are required for the WTH system, and higher fuel consumption with the WTH system machines than with the CTL harvesting system. In addition, labor costs are higher for WTH because more operators are needed.
3.2. Environmental impact assessment

Based on the life cycle inventory data, calculated energy consumption and GHG emissions are presented in Tables 3-5. Compared with more mechanized systems (CTL and WTH), chainsaws/cable skidder system leads to higher energy consumption and GHG emissions because of significantly lower productivities. The feller-buncher system consumes more fossil fuels, resulting in high levels of environmental impacts.

Table 3. Environmental impacts of the CTL harvesting system in Michigan.

| Treatment     | Forest type                  | Emissions (kg CO₂eq/tonne) | Energy (MJ/tonne) |
|---------------|------------------------------|----------------------------|------------------|
| 30% cut       | Natural hardwoods            | 14.58                      | 211.32           |
| (selective)   | Mixed hardwood/softwood      | 12.76                      | 188.82           |
| 70% cut       | Natural softwoods            | 12.41                      | 184.47           |
|               | Softwood plantations         | 10.78                      | 164.23           |
| Clearcutting  | Natural hardwoods            | 11.98                      | 179.20           |
|               | Mixed hardwood/softwood      | 10.90                      | 165.82           |
|               | Natural softwoods            | 10.58                      | 161.78           |
|               | Softwood plantations         | 9.95                       | 154.07           |
|               | Natural hardwoods            | 9.01                       | 142.34           |
|               | Mixed hardwood/softwood      | 8.77                       | 139.35           |
|               | Natural softwoods            | 8.21                       | 132.51           |
|               | Softwood plantations         | 7.21                       | 120.14           |

Table 4. Environmental impacts of the WTH system in Michigan.

| Treatment     | Forest type                  | Emissions (kg CO₂eq/tonne) | Energy (MJ/tonne) |
|---------------|------------------------------|----------------------------|------------------|
| 30% cut       | Natural hardwoods            | 23.47                      | 313.44           |
| (selective)   | Mixed hardwood/softwood      | 23.88                      | 318.54           |
Table 5. Environmental impacts of the MMH system in Michigan.

| Treatment       | Forest type                  | Emissions (kg CO₂eq/tonne) | Energy (MJ/tonne) |
|-----------------|------------------------------|----------------------------|-------------------|
| 30% cut (selective) | Natural hardwoods          | 20.88                      | 264.14            |
|                 | Mixed hardwood/softwood     | 21.68                      | 277.92            |
|                 | Natural softwoods           |                            |                   |
|                 | Mixed hardwood/softwood     |                            |                   |
|                 | Natural softwoods           |                            |                   |
|                 | Softwood plantations        |                            |                   |
| 70% cut (shelterwood) | Natural hardwoods          | 19.24                      | 243.88            |
|                 | Mixed hardwood/softwood     | 21.68                      | 274.02            |
|                 | Natural softwoods           | 22.43                      | 283.31            |
|                 | Softwood plantations        | 23.97                      | 306.38            |
| Clearcutting    | Natural hardwoods           | 21.12                      | 267.15            |
|                 | Mixed hardwood/softwood     | 22.10                      | 279.25            |
|                 | Natural softwoods           | 22.62                      | 372.38            |
|                 | Softwood plantations        | 25.72                      | 379.29            |

4. Sensitivity analysis and discussion

A sensitivity analysis was conducted to explore the importance of input variables to harvesting cost determination, energy demand and GHG emissions estimation. Productivity estimate for different harvesting equipment configurations is a key input for all three indicators. Additional key inputs to harvesting cost include machine purchase price, salvage value, economic life in years, scheduled hours per year, expected utilization rate, repair and maintenance cost, interest insurance and taxes, labor rate and fringe, fuel and lubricants, etc. Other key inputs to environmental impact include a series of intensity factors, such as GHG intensity of fossil fuel consumption, lubricants, machine construction, repair and maintenance. The input variables are increased or decreased by 10%. Harvesting cost, energy demand and GHG emissions were recalculated and compared to the base case.

4.1. Sensitivity analysis of harvesting cost

The sensitivity analysis was performed for the CTL harvesting system. The key inputs to harvesting cost were classified into three categories: system data (productivity and labor rate), data for CTL harvester, and data for forwarder. The analysis of results is illustrated in Figure 4. Note that harvest and forest types were not differentiated because the percent changes in harvesting cost are not affected by harvest types as well as forest types. Figure 4 shows that productivity had the largest impact on harvesting cost, while large machinery repair and maintenance had the smallest, as would be expected. Besides machinery purchase price, yearly scheduled hours and expected utilization (%) also had large impacts on the results.
4.2. Sensitivity Analysis of Environmental Impacts

The sensitivity analysis of environmental impacts was conducted for the CTL harvesting system. The input variables considered were productivity, fuel and chemical inputs, and the corresponding GHG emissions or energy demand intensity factors. The analysis results are illustrated in Figure 5. Note that harvest and forest types were not differentiated because the percent changes in energy demand or GHG emissions was not affected by these dimensions. Figure 5 highlights how productivity, fuel use as well as fuel factors had greater impacts on energy consumption and GHG emissions. Additionally, productivity had a positive impact while fuel use and its intensity factor had negative impacts. All other input variables (e.g., oil/lubes, grease, and large machinery repair and maintenance) had smaller impacts as would be expected. Note that in Figure 5, fuels or chemicals use were placed in the same group as their corresponding intensity factors (e.g., fuel use and its emission factor, oil/lubes and its energy demand factor). This is because the two items are multiplied in the model for calculating energy demand or GHG emissions, and thus they have the same degree of impacts on the results.

Figure 4. Sensitivity analysis for significant inputs to harvesting cost
5. Summary and conclusions

By collecting data from literature and database sources, an assessment of economic, energy demand and GHG emissions was performed for forest-based biomass harvesting in Michigan. The assessment differentiates harvesting systems (CTL, WTH, or MMH), harvest types (30%, 70%, or 100% cut), and forest types (hardwoods, softwoods, mixed or softwood plantations) that characterized Michigan’s logging industry. It is believed that this is the first time explicit analysis of these three indicators for Michigan’s harvesting activities has been conducted. The machine rate method was employed to determine harvesting costs. A life cycle inventory was applied to estimate energy demand and GHG emissions for different scenarios, considering energy and material inputs (diesel, machinery, etc.) and outputs (emissions) in each process (e.g., cutting, skidding/forwarding, slashing, etc.). Sensitivity analysis was performed for significant input variables to the harvesting operation to explore their importance. The input variables were increased or decreased by 10%. Harvesting cost, energy demand and GHG emissions and compared to the baseline. Several conclusions were drawn as follows:

- Harvesting cost for MMH system is higher than the more mechanized systems (CTL and WTH) across most forest and harvest types.
- For CTL and WTH mechanized systems, average harvesting cost decreased as removal intensity increased from 30% to 100%, with WTH slightly higher than CTL in most cases except for shelterwood cutting on natural hardwoods and clearcutting operations on natural hardwoods and mixed hardwood/softwood.
- Compared with more mechanized systems of CTL and WTH, the MMH system leads to higher GHG emissions and energy demand due to significantly lower productivities.
- The WTH system consumes more fossil fuels, resulting in high levels of environmental impacts.
- Productivity had the largest impact on harvesting cost, while large machinery repair and maintenance had the smallest. Besides, machinery purchase price, yearly scheduled hours and expected utilization (%) also had large impact on the results.
Productivity, fuel use as well as fuel factors had huge impacts on energy consumption and GHG emissions, except that productivity had a positive impact while fuel use and its intensity factor had negative impacts. All other input variables (e.g. oil/lubes, grease, and large machinery repair and maintenance) had small impact.

Percent changes in harvesting cost, energy demand and GHG emissions are regardless of harvest types as well as forest types.

Fuels or chemicals use and their corresponding intensity factors (e.g., fuel use and its emission factor, oil/lubes and its energy demand factor) have the same degree of impacts on energy demand and GHG emissions.

This study is believed to be the first to conduct an explicit assessment of the three indicators (cost, energy and emissions) for Michigan’s harvesting activities differentiating harvesting systems, harvest types, and forest types. Most previous LCAs of biofuels produced from various biomass feedstocks focused on environmental performance of producing and supplying feedstocks [7,10-14] without paying much attention on economic efficiency. Moreover, the estimation of harvesting/forwarding activities were based on the assumption of using cut-to-length harvester/forwarder only [12] or whole tree harvesting system only [13]. Other studies did not differentiate harvest types (assuming 100% clear-cutting) [12] or forest types for environmental impact assessment [14]. This research increases the scope of prior work and expands the body of knowledge in this area.

For future work, a life cycle cost, energy efficiency and GHG emissions would be performed for other stages of forest-based biomass supply chain, including the upstream of biomass transport and storage and the downstream of biofuel production and distribution. An integrated analysis of the entire supply chain may be also conducted.

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