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Measuring the Regional Availability of Forest Biomass for Biofuels and the Potential of GHG Reduction

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Abstract: Forest biomass is an important resource for producing bioenergy and reducing greenhouse gas (GHG) emissions. The State of Michigan in the United States (U.S.) is one region recognized for its high potential of supplying forest biomass; however, the long-term availability of timber harvests and the associated harvest residues from this area has not been fully explored. In this study time trend analyses was employed for long term timber assessment and developed mathematical models for harvest residue estimation, as well as the implications of use for ethanol. The GHG savings potential of ethanol over gasoline was also modeled. The methods were applied in Michigan under scenarios of different harvest solutions, harvest types, transportation distances, conversion technologies, and higher heating values over a 50-year period. Our results indicate that the study region has the potential to supply 0.75–1.4 Megatonnes (Mt) dry timber annually and less than 0.05 Mt of dry residue produced from these harvests. This amount of forest biomass could generate 0.15–1.01 Mt of ethanol, which contains 0.68–17.32 GJ of energy. The substitution of ethanol for gasoline as transportation fuel has potential to reduce emissions by 0.043–1.09 Mt CO_{2eq} annually. The developed method is generalizable in other similar regions of different countries for bioenergy related analyses.

Keywords: timber; harvest residues; ethanol; GHG savings; Michigan

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1. Introduction

In the United States (U.S.), transportation accounts for 69.8% of U.S. petroleum consumption [1] and 27% of total greenhouse gas (GHG) emissions in 2013. The transportation sector is the second largest contributor of U.S. GHG emissions following the electricity sector [2]. Increasing concerns that are associated with depletion of fossil fuels and global warming have imposed pressure on companies in the U.S. transportation sector and stimulated the evaluation of different alternative energy resources [3,4]. Bioethanol and biodiesel from lignocellulosic biomass (e.g., agricultural residues, woody biomass, and energy crops) could serve as partial replacement for petroleum based gasoline and diesel, respectively, and therefore, would help to minimise GHG emissions and achieve environmental goals.

There is a vast literature on biomass potential analysis worldwide. Hernandez et al. [5] assessed the theoretical and technical potential of available woody biomass for energy use with a regional case study in the north and central-south part of Mexico. Crawford et al. [6] conducted a spatial assessment of potentially available biomass for bioenergy in Australia in 2010, 2030, and 2050 for different types of biomass sources, including pulpwood and residues etc. Zhang et al. [7] explored the quantity and distribution of forest biomass in China based on forestry statistics data. Woch et al. [8] studied the potential of forest woody waste biomass for energy use in eastern Poland.

The State of Michigan (MI) offers significant potential for supplying forest-derived feedstocks [9] with annual growth far exceeding removals plus mortality in most timberland areas [9,10]. At the same time, a recent decline in traditional roundwood industries (e.g., pulp and paper, lumber) have revealed a new opportunity for the sustainable use of forest resources [11]. However, the estimates of feedstock availability suffer substantial uncertainties [12,13], such as the landowners' willingness and acceptance to harvest [14–16], the accessible with roads to harvest [17], the economic performance of feedstock supply chain (consisting of feedstock harvesting, transportation, and storage, etc.), as well as the delivered feedstock price [9,18]. All of these constraints should be considered when approximating long term biomass availability and estimating the corresponding biofuels potential.

Jakes and Smith [19] predicted Michigan's timber yields between 1980 and 2010. Sherrill and MacFarlane [20] assessed potential availability of urban forests, including wood residues and saw timber, for a 13-county region of Lower Michigan in 2007. MacFarlane [21] extended prior research in 2008 by examining potential urban tree biomass availability and the associated implications for energy production, carbon sequestration, and sustainable forest management. Mueller et al. [22] provided a snapshot of Michigan's woody biomass supply in 2010. Brunner et al. [23] assessed cellulosic ethanol production from the perspective of landscape scale net carbon, which is the tradeoff between the displacement of fossil fuel carbon emissions by biofuels and the high rates of carbon storage in aggrading forest stands. Gahagan et al. [24] evaluated carbon fluxes, storage, and harvest removals through 60 years of stand development in red pine plantations and mixed hardwood stands in Northern Michigan. Other studies revealed the availability of timber and residue in the Lake States region of Minnesota (MN), Wisconsin (WI), and Michigan (MI) [3,19]. Kukrety et al. [3] assessed sustainable forest biomass availability, likely harvest levels over a 100-year period, and bioenergy implications for the northern Lake States region. Becker et al. [19] examined current and projected resource needs for forest biomass in the Lake States.

There are also extensive scientific studies investigating GHG emissions mitigation potential of biomass resources worldwide. For example, Weldemichael and Assefaab [25] reported 11–15% of GHG emissions reduction by 2030, with the utilization of agricultural and forest biomass resources for energy production in Alberta. Veronika et al. [26] developed a GHG emission mitigation supply curves assuming a large-scale biomass use in Poland. Winchester and Reilly [27] assessed the contribution of biomass to emissions mitigation (16% less in basic policy case than the reference case) under a global climate policy.

In view of these studies, it is found that prior published research lacks a comprehensive study approximating long-term forest biomass availability and the associated uncertainties in the State of Michigan. In this study, the long-term (2015–2065) timber availability was derived from previous harvest trends for the Michigan. Harvest residues associated with growing stock volume cut or knocked down during harvest (including branches and tops) were approximated using the developed formulas considering a few of influential factors, including harvest types of all merchantable timber and the associated residue management options, and residue collection rate etc. Then, the potential forest biomass utilization for ethanol production and GHG reduction were also examined using the developed methods.

2. Materials and Methods

2.1. Study Area

The State of Michigan has a large biomass resource base that could be used as feedstock for biofuel facilities. In 2009, more than half (54%) of Michigan's land area was covered by forests [28]. The map of Michigan (Figure 1) shows the forest distribution on region basis in Michigan. A description of the study theme in this study is presented in Figure 2.

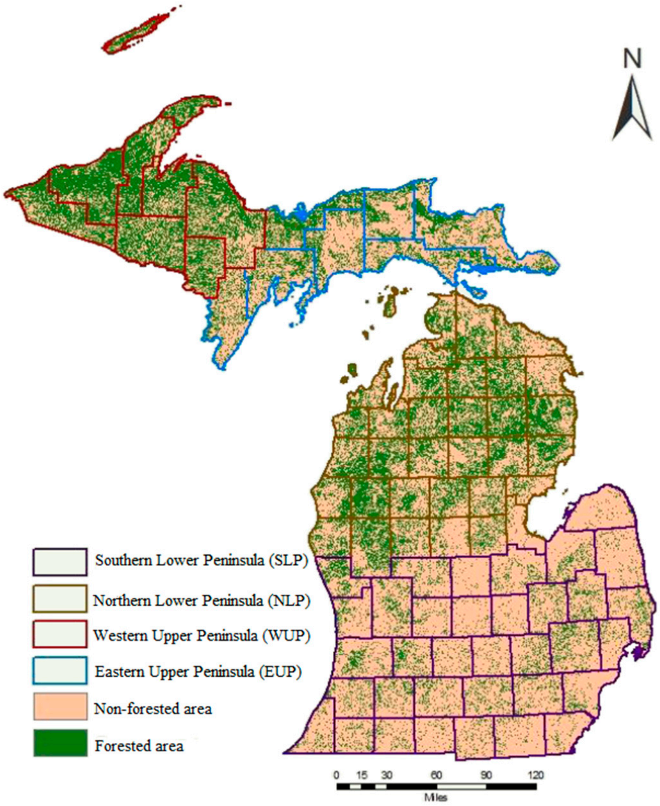

Figure 1. Michigan regions and forest (Based on study of [29]).

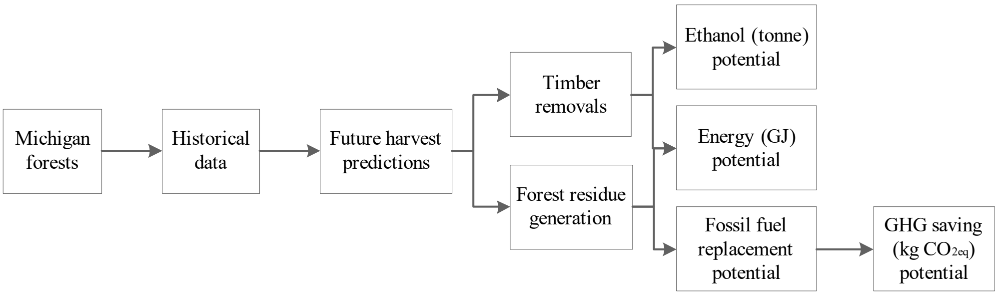

Figure 2. A description of the study theme.

2.2. Timber Volume Assessment and Prediction

Timber volume serves as a reasonable, though incomplete, measure of biomass [30]. Time trend analyses were employed by the U.S. Department of Agriculture (USDA) Forest Service timber assessments to understand how the timber supply today as it relates to the previous 50 years. The timber harvest trends were predicted by the functional form [31]:

$$\ln(HARVEST)_t = a_0 + a_1 TIME \tag{1}$$

where the dependent variable is the natural log of total harvest at time t, a_0 is a constant, a_1 is the slope of the trend line (rate of change of harvest divided by rate of change of time), and *TIME* is the number of years since the start of the sample (current year less t_0 the date of the initial year) [31].

To use the above formula for long-term timber harvest estimates and forecasts, 26 years (1990–2015, fiscal year (1 October–30 September) annual timber sales data (in cords) were collected from literature. Cord is a volume unit commonly used in North-America. The Statewide Forest Resource Plan of 1983 promoted "stabilized timber supplies from public land", resulting in a stabilized forest products industry in Michigan [32]. This plan supports the suitability of using Equation (1) to estimate Michigan's timber harvest trend. As shown in Figure 3, a probability distribution describing the likely future timber harvests in Michigan by 2065 (over the 50-year time period) was created using the historic data collected. The calculated coefficients a_0 = 13.428 and a_1 = 0.0077. Thus, the Equation (1) can be rewritten as:

$$Q^{T}_{timber} = e^{13.428+0.0077TIME} \tag{2}$$

where Q^{T}_{timber} (cords) is the annual timber harvest in year T and $TIME$ is the number of years since 1990.

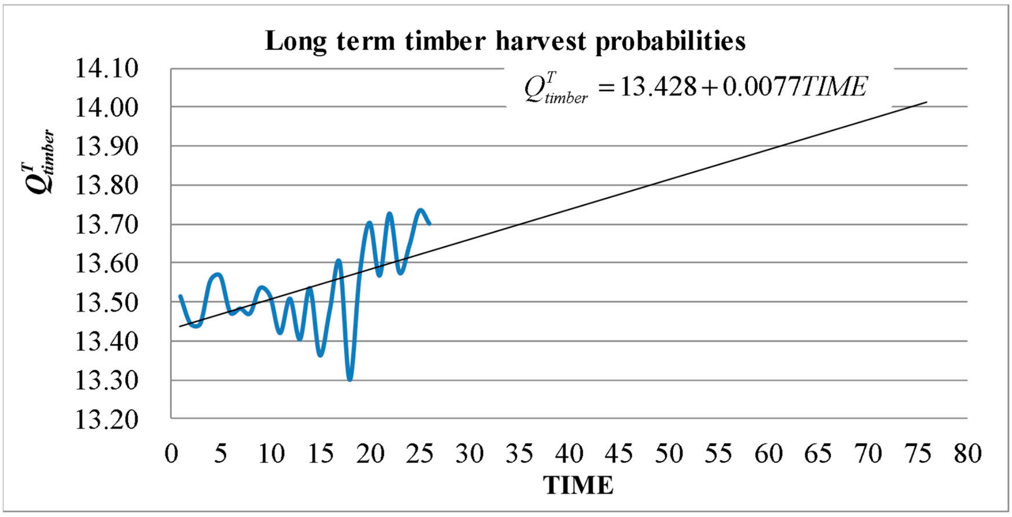

Figure 3. Graph showing the harvest trend developed from historic data for creating a probability distribution describing likely future harvests in Michigan.

2.3. Harvest Residues Estimation

Harvest residues are those associated with growing stock volume cut or knocked down during harvest (including branches and tops) [12]. In most cases, harvest residues are left at the harvest site, while only a limited quantity is collected from the landing point for energy purposes [33]. As a result, harvest residues are among the largest unused feedstock [19] with annual growth far exceeding removals [3], which presents an opportunity to increase harvest rates for strategic, economic, and forest health reasons [34]. The study [35] estimated logging residues by determining the proportional volume of tops and limbs in growing stock trees, which is approximately 17% of growing stock merchantable bole volume (tops/bole) for softwoods and 29% for hardwoods. In this study, the estimate method can be revised as the corresponding proportional volume of tops and limbs in timber harvest volume. Hardwoods and softwoods ratio was estimated to be 3:1 in Michigan based on the statistical information from [36].

Further, to estimate the quantity of logging residues for new biofuel facilities, it is critical to differentiate harvest types of all merchantable timber, since it is not a practical option by assuming clearcut treatment of all removals [37]. The main harvest types characterizing the logging industry in Michigan include [37,38]: (1) clearcutting all merchantable timber; and, (2) partial removal treatments (including 70% shelterwood and 30% selective cut). On the other hand, management of logging residue is also an important part of timber sale planning, which involves controlling the amount of residue remaining on the ground [39]. The residue management options (%) by harvest types were collected, as shown in Table 1. To explore use of residue in biofuel production and GHG reduction potential in

Michigan, a residue collection rate of 65% (onsite retention of 35%) was assumed for the removing residue management options in Table 1.

Table 1. Residue management options (%) by harvest types in Michigan (Based on study of [37]).

Residue Management Options	Symbol	Percent
Clearcut and leave residue	H_{cl}	27.8%
Clearcut and remove residue	H_{cr}	9.9%
Partial removal and leave residue	H_{pl}	50.9%
Partial removal and remove residue	H_{pr}	9.7%
Other method	H_{o}	1.7%
The sum		100%

Based on above assumptions, the quantity of logging residues can be estimated using the formula:

$$Q^T_{residue} = Q^T_{timber}(H_{cr} + H_{pr})(P^{hard}_{timber}p^{residue}_{hard} + P^{soft}_{timber}p^{residue}_{soft})\theta \quad (3)$$

where $Q^T_{residue}$ is the annual collectable residue volume (cords) in year T. P^{hard}_{timber} is the proportion of hardwoods in Michigan's timber harvest and P^{soft}_{timber} is the corresponding percent for softwoods.$p^{residue}_{hard}$ is the proportion of hardwoods in timber harvest, and $p^{residue}_{soft}$ is the corresponding percent for softwoods. θ is the residue collection rate.

For Michigan's case, the Equation (3) is simplified as:

$$Q^{T,MI}_{residue} = Q^T_{timber}(9.9\% + 9.7\%) \times (75\% \times 29\% + 25\% \times 17\%) \times 65\% = 0.033Q^T_{timber} \quad (4)$$

The Equation (4) shows that harvest residue collectable is only 3.3% of timber harvest. This is due to the low percent of removing residue options (9.9 + 9.7% = 19.6%) in Table 1. Most of the cases, logging residues are left onsite for retention.

2.4. Implications of Use for Ethanol Production and GHG Savings

2.4.1. Biomass Conversion Technologies

Different conversion technologies are available to convert forest and wood residues into a variety of biofuels and chemicals [40]. Conversion technologies of biomass to biofuels fall into two principal categories: thermo-chemical and bio-chemical technologies [41], which closely investigated several thermochemical and biological conversion processes employing three important metrics: mass ratio, energy ratio, and energy efficiency. The calculated metrics of ethanol from hardwood and softwood through different conversion processes are presented in Tables 2 and 3.

Table 2. Mass ratio of ethanol from hardwood and softwood through different conversion processes (Based on study of [41]).

Ethanol by Thermo-Chemical Process		
Hardwood	Softwood	Comments
0.49	0.52	Without catalytic methane reformation
0.73	0.76	With catalytic methane reformation
0.58	-	With feedstock used for process energy
Ethanol by Biochemical Process		
0.195	0.205	-

Table 3. Energy ratio of ethanol from hardwood and softwood through different conversion processes (Based on study of [41]).

Hardwood	Softwood	Comments
Ethanol by Thermo-Chemical Process		
0.58	0.6	Without catalytic methane reformation
0.86	0.88	With catalytic methane reformation
Ethanol by Biochemical Process		
0.23	0.215	-

Since there was no mass and energy ratio information provided for woody residue, the two metrics for the residues were assumed to be the same as timber. For Michigan's case, this assumption stands because residue volume accounts only 3.3% (obtained from Equation (4)) of timber volume.

2.4.2. Long Term Ethanol Probabilities

The estimates for the current and potential use of forest biomass for biofuel are based on volumes (cords). Since green weights are imprecise and highly variable, cubic foot volumes or dry weight are assumed to be more reliable estimates of inventory, growth, and removals and changes over time [11]. Therefore, a conversion to oven-dried tons (ODT) was calculated to convert the timber and residue volumes (cords) to dry weights. The conversion factor is 1.21 ODTs/cord, which is the average conversion factor that is used in the Forest Age Class Change Simulator (FACCS) simulation model [42]. Since 1 short ton = 0.907 metric tonne, the conversion factor is recalculated as 1.21 × 0.907 = 1.097 tonnes of dry matter per cord. By assuming that forest residues have the same conversion rate with timber roundwood, the mass of ethanol (M_{EtOH}^{T}, tonne) can be calculated as:

$$M_{EtOH}^{T} = 1.097(Q_{timber}^{T} + Q_{residue}^{T})(P_{timber}^{hard}\alpha_{hard}^{mr} + P_{timber}^{soft}\alpha_{soft}^{mr}) \tag{5}$$

where the α_{hard}^{mr} represents the mass ratio of ethanol from hardwood and α_{soft}^{mr} is the one from softwood.

With a density of 0.789 tonne/m^3 of ethanol [43], the tonnage of ethanol can be converted to liters through:

$$V_{EtOH}^{T} = 1,390(Q_{timber}^{T} + Q_{residue}^{T})(P_{timber}^{hard}\alpha_{hard}^{mr} + P_{timber}^{soft}\alpha_{soft}^{mr}) \tag{6}$$

where V_{EtOH}^{T} is the predicted volume (liters) of ethanol in year T.

For Michigan's case, Equation (4) and the values of P_{timber}^{hard} and P_{timber}^{soft} are substituted into Equations (5) and (6), the predicted mass (tonnes) and volume (liters) of ethanol in year T can be obtained by:

$$M_{EtOH}^{T,MI} = Q_{timber}^{T}(0.85\alpha_{hard}^{mr} + 0.28\alpha_{soft}^{mr}) \tag{7}$$

$$V_{EtOH}^{T,MI} = Q_{timber}^{T}(1,077\alpha_{hard}^{mr} + 355\alpha_{soft}^{mr}) \tag{8}$$

2.4.3. Long Term Energy Probabilities

Based on forest biomass predictions, the energy (E_{EtOH}^{T}, GJ) contained in the ethanol produced can be calculated as:

$$E_{EtOH}^{T} = 1.097(Q_{timber}^{T} + Q_{residue}^{T})(P_{timber}^{hard}\alpha_{hard}^{mr}\beta_{hard}^{er}HHV_{hard} + P_{timber}^{soft}\alpha_{soft}^{mr}\beta_{soft}^{er}HHV_{soft}) \tag{9}$$

where β_{hard}^{er} represent the energy ratio of ethanol from hardwood and β_{soft}^{er} is the one for softwood. HHV_{hard} (MJ/kg) is higher heat value for hardwood and HHV_{soft} (MJ/kg) is the one for softwood.

For Michigan's case, the long term energy probabilities can be calculated as:

$$E_{EtOH}^{T,MI} = Q_{timber}^{T}(0.85\alpha_{hard}^{mr}\beta_{hard}^{er}HHV_{hard} + 0.28\alpha_{soft}^{mr}\beta_{soft}^{er}HHV_{soft}) \tag{10}$$

2.4.4. GHG Savings Potential

For a more accurate estimation of GHG-related benefits of forest-based ethanol over gasoline, it is necessary to account for the emissions occur throughout the life cycle of ethanol from forest biomass pre-treatment and collection, transportation to biorefinery, conversion to ethanol, transportation to terminals, and the end use of ethanol. While the emissions from the end use or burning of ethanol are assumed to be carbon neutral because they are equivalent to the emissions that are captured during tree growth [44]. Therefore, the total annual GHG savings (GS^T, kg CO_{2eq}) can be expressed as the annual emission credits (G_{gas}^T, kg CO_{2eq}) obtained from replacing current gasoline minus the life cycle emissions (G_{gas}^T, kg CO_{2eq}) of ethanol in year T.

$$GS^T = G_{gas}^T - G_{EtOH}^T \tag{11}$$

The annual GHG emissions (G_{gas}^T and G_{EtOH}^T) is calculated by multiplying the amount of energy with an emission factor. The emission factor associated with combusting gasoline is 74.2 kg CO_{2eq}/GJ) [45]. The emission factor for ethanol takes the median life cycle emission per energy unit [25].

3. Results and Discussion

3.1. Potential of Biomass

The estimates for the current and potential use of forest biomass (timber, residues, and total in dry tonnes) for biofuel are illustrated in Figure 4. It is clear that timber is the major source of forest biomass and the availability of it increases steady in the foreseeable future. Harvest residues account for only a small proportion of the forest biomass and increase slowly over time. The results indicate that the study region has the potential to supply 0.75–1.4 Megatonnes (Mt) dry timber annually, and less than 0.05 Mt of dry residue produced from these harvests. These results are significantly smaller than that of [3], which did not consider the impacts of different harvest types on collecting residues.

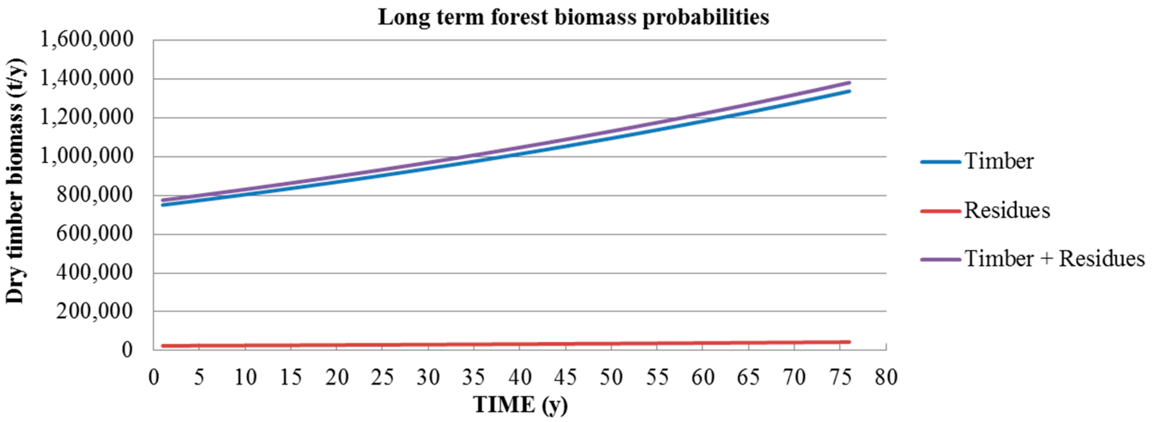

Figure 4. Long term forest biomass probabilities in Michigan.

3.2. Potential of Ethanol

Figure 5 presents the long term ethanol (tonne) probabilities in three scenarios: (1) ethanol by thermo-chemical process without catalytic methane reformation, (2) ethanol by thermo-chemical process with catalytic methane reformation, and (3) ethanol by biochemical process. As it can be seen in Figure 5, long term ethanol production shows steadily increasing trends for all three scenarios. As expected, the mass of ethanol in the scenario (1) achieves the highest when comparing with the other two scenarios due to no catalytic methane was reformed in the conversion process. The low mass ratio in scenario (2) resulted in low tonnage of ethanol production.

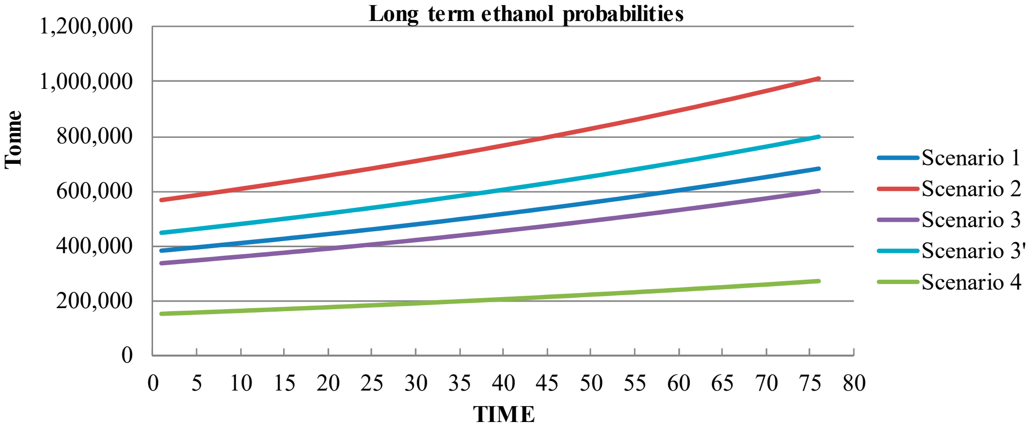

Figure 5. Long term ethanol probabilities in Michigan.

3.3. Potential of Energy and Emission Savings

According to [11], the commercial timber species within the Kinross supply region are categorized into five hardwood groups (Aspen, Maple, Oak, Upland Hardwoods, and Lowland Hardwoods) and three softwood groups (Pine, Upland Softwoods, and Lowland Softwoods). The Kinross supply region covers the Western Upper Peninsula (WUP, refer to Figure 1 for Michigan regions) in total, the Eastern Upper Peninsula (EUP) in part, and the Northern Lower Peninsula (NLP) in major part. As it can be seen from the Figure 1, the three regions (WUP, EUP, and NLP) are the main forest regions in Michigan. Thus, it is reasonable to take the timber species within the Kinross supply region as the timber species in Michigan. Since the HHV variation between species is usually smaller than the variations within one species [46], the average HHV (19.3 MJ/kg) collected for maple is used as the HHV for hardwood and the average HHV (20.9 MJ/kg) for pine as the HHV for softwood in this study. The results were illustrated in Figure 6. As expected, scenario 2 resulted in the most energy production due to the high mass and energy ratios.

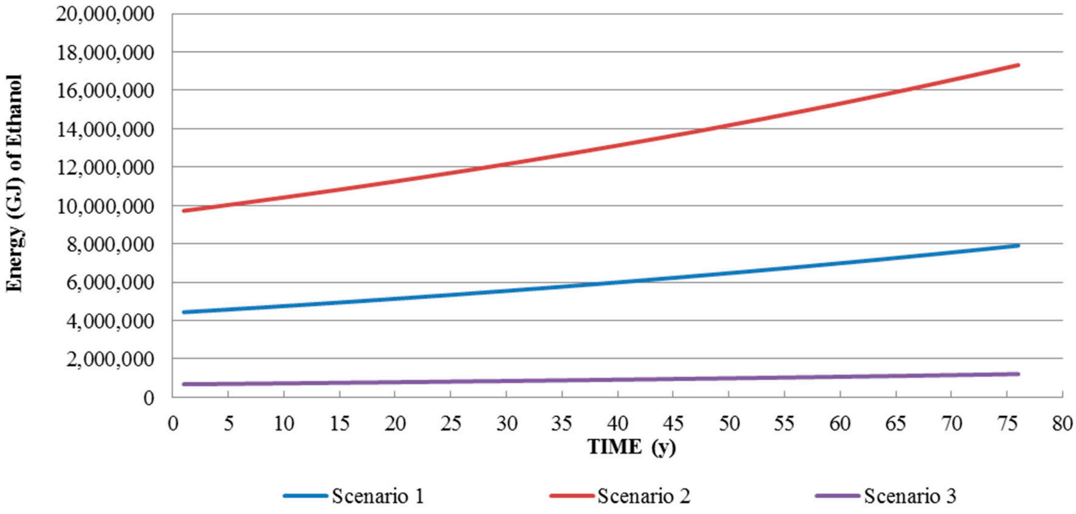

Figure 6. Long term energy probabilities of ethanol from forest biomass in Michigan.

Based on the long term energy probabilities of ethanol as shown in Figure 6, the total GHG savings are calculated and the predication results are shown in Figure 7.

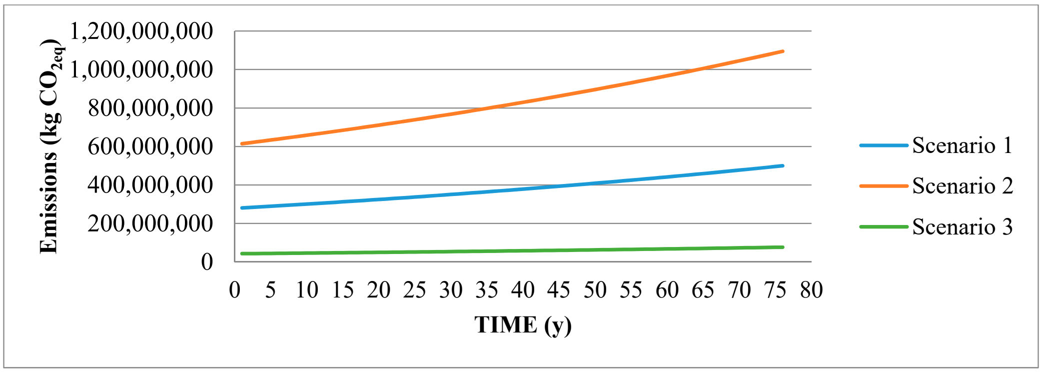

Figure 7. Long term emission savings probabilities of replacing gasoline with ethanol from forest biomass in Michigan.

4. Discussion

There is a vast of literature exploring the estimation methods of biomass potential. Since this study focused on timber and corresponding harvest residues instead of other types of biomass, only the literature studying forest biomass availability were examined. When compared to the volume estimation methods that are developed in this study, the 1998–1999 Silvicultural Analysis established an accounting framework and applied it to a 10-year (1999–2008) projection of the State Forest inventory in Michigan [32]. Kukrety et al. estimated the potential availability of roundwood and harvest residues using FIA inventory data and age-class progression techniques combined with average stand growth and yield models and applied it to the Lake States region [3]. To estimate potential annual yield from urban trees, it is a general method by evaluating the rate of urban trees becoming available for utilization. A vast of literature of potential wood biomass availability focused on growth rates of different vegetation type [47], while MacFarlane used mortality rate of urban trees and conducted a regional study of the potential availability of urban wood biomass in a 13-county area of Michigan [21]. Adams integrated published specific gravity and biomass distribution data with bolewood volumes predicted from regression equations relating these volumes to stand height and basal area to estimate forest biomass in northern lower Michigan [48].

As discussed above, the value for the prediction of biomass, ethanol, energy and emission savings vary depending up on regional parameters, scope of the study, assumptions made, and other factors that are considered for analysis [25]. This study predicted timber volume by collecting historical timber sales data from literature combing the time trend analyses from [31]. The energy potential was estimated based on heating value, which is a popular method for quality analysis of biomass [49]. This study conducted a comprehensive study approximating long-term forest biomass availability and associated energy production and emissions analysis to fill the gap by taking Michigan as one study region. The derived results are comparable to these studies discussed above.

5. Conclusions

Strong demand for oil in the United States (U.S.) for the transportation sector, multiple societal issues, including climate change concerns, heavy air pollution, high dependence on imports, and a multitude of security concerns have stimulated research in finding methods to reduce the use of fossil fuels for transportation fuel by substituting with renewable biomass. However, there is a lack of comprehensive regional estimates of available biomass, hindering the opportunity to maximise benefits. Using the State of Michigan in the United States as a case study, the long term harvest probabilities of timber were evaluated based on historic harvest data, as well as the implications of collecting residues and their use for ethanol production. The emission benefits of replacing fossil fuel with ethanol were also evaluated. Uncertainties that are considered include harvest solutions, harvest types, transportation distances of biomass/biofuel, biomass conversion technologies, and higher heating values, etc. The results indicate that the study region has the potential to supply 0.75–1.4 Mt dry timber annually and less than 0.05 Mt of dry residue produced from these harvests. This amount of forest biomass could generate 0.15–1.01 Mt of ethanol, which contains 0.68–17.32 GJ of energy. The substitution of ethanol for gasoline as transportation fuel has potential to reduce GHG emissions by 0.043–1.09 Mt CO_{2eq} annually. In addition to promoting energy security and reducing GHG emissions, the use of forest residues for energy would create additional income and employment opportunities in the forest based sector.

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