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Modeling the importance of biomass qualities in biomass supply chains for bioenergy production

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Abstract

A tactical-operational level quantitative model can be an important decision support tool for bioenergy producers. Goal programming approach can help analyze the costs and volume implications of various competing goals in terms of biomass characteristics on part of the bioenergy producers. One cost and six quality characteristics goals, namely moisture and ash contents, and thermal values of two types of biomass (forest harvest residue and un/under-utilized species) are selected for the four bioenergy producers in northwestern, Ontario, Canada. We run four models cenarios: i) benchmark total cost and ceilings of mean values of six biomass qualities (Initial Goals), ii)relaxing the quality goals by 10% from the Initial Goals scenario, iii) increasing the conversion efficiency by 10%, and iv) all goals as in Initial Goals except the Atikokan Generating Station (AGS)being supplied with only un/under-utilized biomass. The smaller power plants have relatively less per unit biomass procurement cost. While per unit procurement costs increased, the total costs and biomass volume required to produce the same amount of bioenergy for each power plant decreased in all scenarios compared to the benchmark costs. The goal programming approach, and the results thereof are found to be useful in making effective decisions in the biomass supply chains for bioenergy production.

Keywords: Combined heat and power (CHP); Decisions support system; Forest harvest residue; Northwestern Ontario; Supply chain modeling; Woody biomass.

1. Introduction

Globally forest land-use has significant potential to reduce greenhouse gas (GHG) emissions if managed and used properly. However, it can manifest differently in different regions of the globe depending on the level of development. For example, halting deforestation and forest/soil degradation and enhancement of carbon pool in managed forest ecosystems in developing countries can reduce the GHGs emissions to a large extent [1-3]. Similarly, use of forest residues and un-merchantable trees (mainly under-utilized hardwood species) from sustainably managed forests for bioenergy production in the developed world can replace the fossil fuel-based energy usages, thereby helping reduce the present level of GHGs emissions. Further, use of woody biomass for bioenergy production has many environmental and socioeconomic benefits –this being sustainable renewable and CO_2-neutral resource, reducing risk of forest fire events, increased rural employment and income, etc. [4, 5]. Nonetheless, bioenergy production faces many emerging challenges that include uncertainty of biomass feedstock supply due to its sparse distribution over space and time, not yet fully developed biomass and bioenergy markets, relatively higher costs of production if the environmental and other benefits not taken into account which is the case at present [5, 6]. Moreover, as more biomass-based power plants come into operation in the near future there would be higher volume demand for biomass feedstock that results in an increase in transportation distance, and hence the higher biomass procurement costs [6-8]. In order to analyze decisional problems of such supply/value chains strategic, tactical and operational level planning models are used depending on the scales in terms of planning horizons in general. In this context, a tactical-operational level goal programming (GP) model can be an important decision tool for bioenergy producers in general. The modelling approach in this study, therefore, exemplifies the biomass procurement cost structures under various resource constraints with varying biomass quality, and procurement cost goals on part of the power plants under various model scenarios.

Globally, fossil fuels burning and land-use changes are the major contributors for the GHG emissions [2]. In this context, various international climate policies have exerted pressure on reducing GHG emissions for developed countries in which the Canadian government has also made a commitment to reduce GHG emissions from its major industrial sectors. The forest products industry of Canada, which requires a huge amount of energy to operate, has been a leader in utilizing bioenergy (e.g., burning black liquor and hog fuel for a major part of their energy needs). Beyond the forest industry, several independent power plants generate electricity from forest biomass. For example, utilization of wood biomass for bioenergy production has recently increased dramatically in northwestern Ontario (NWO) with four major energy plants with estimated biomass demand of about 2.21 million green tonnes [9]. Currently, three major combined heat and power(CHP) plant developments in NOW have the potential to use forest biomass feedstock for bioenergy production. These include Resolute Forest Products Thunder Bay CHP Plant (ABTB), Resolute Forest Products Fort Frances CHP Plant (ABFF) and Domtar Dryden CHP Plant (DDPP) with different levels of electrical and thermal power production capacities. The Atikokan Generating Station (AGS), another power plant in NWO, is currently being converted to use forest biomass feedstock instead of coal. Its power generating capacity is 230 MW_e, with a plan to run at 10% capacity [10]. With the development of these biomass based bioenergy plants, the entire bioenergy system in the NWO will generate major socio-environmental consequences in terms of reducing GHG emissions and stabilizing the economy of many small rural communities.

The two types of woody biomass used for this study are: FHR - forest harvest residue which includes tops and branches and wood left after stand harvesting; and UUW - un/under-utilized wood which includes un-harvested tree species that are not commercially important for timber. These biomass sources have variable costs and qualities in terms of thermal value, moisture content and ash content. A power plant manager can have various biomass quality goals as well as the cost target so that the plant can be run cost effectively. This kind of decision problem in a biomass supply chain can best be handled by using GP modeling technique. However, we found very few studies on modeling the wood biomass for bioenergy supply chains in Canada that consider multiple goals in terms of biomass qualities. Most of the existing studies focus mainly on optimizing harvesting and transportation of raw material for forest products industries from forest management units (FMUs) to the processing facilities [11, 12].

Our previous study [13] used the goal programming approach to model the cost and quality goals of varied sources of wood biomass. However, that study did not used the engineering equations to endogenize the biomass requirements once the biomass qualities change. The biomass requirements for each of the four plants were fixed instead of biomass being the function of amount of energy productions. This was modeled such as the information available at the time was constrained. The main objective of this study is, therefore, to improve upon our previous paper [13] with updated database in order to make the model more practical and policy relevant at operational level for the bioenergy producers. We model the biomass supply chains by using the engineering equation to first decide the amount of biomass (with various physical characteristics) required as function of amount of energies to be produced by each power plant. And then the GP model optimize the amount of 'right' type of biomass to be harvested from the forest cells. We analyze different scenarios relating to various biomass quality goals and technical efficiency change, and their impacts on procurement costs per green tonne and for total biomass for each of the power plant. The variations in quality characteristics (thermal value, moisture and ash contents) of two types of biomass distributed over the productive forest cells derive the total biomass requirement to produce bioenergy at the capacity levels of each power plant. The end results of the entire modelling process are to get to the estimates of costs structures with respect to different sets of goals/targets by different model scenarios. Though the modelling technique in this study is developed for optimizing the biomass supply chains pertinent to the Ontario bioenergy producers, this can be easily adapted to the similar cases elsewhere. Hence, the importance of this work is of global nature in the era of emerging sustainable energy development around the globe in order to mitigate the GHGs emissions.

2. Data and method

2.1 Study area and data

The study area consists of 18 forest management units (FMU) west of Lake Nipigon in NWO where four power plants are running with biomass as their feedstock (Figure 1). The NWO study area is 167,184 km^2, with an annual average harvest of 60,867 ha (2002-2009) which is 0.61% of the productive forest area per year. GIS data related to forest areas and depleted forest for the period 2002-2009 were collected from Land Information Ontario, Sustainable Forest Licence (SFL) holders, and consultant companies in the formats of Shapefile and Geodatabase. The entire modeling system undergoes into two steps. First a database relating to the logistics costs to transport the biomass from each forest cells to the four power plants are estimated by road network optimization model [9]. Then the database thus obtained is used in GP model to estimate the optimal costs structures for biomass supply chains for each of the power plant.

Figure 1. Map of study area (Source: [14])

In the first step, the original vector data is converted to raster and finally to spatial database text files for the entire research area using Arc GIS software. Three main spatial layers (land use, forest depletion and cost layers) were prepared on a raster grid size of 1 km×1 km (1 km^2), and this study examines 20,315 productive forest cells where the timber harvesting activities occurred from 2002 to 2009. The detailed methodology for estimating forest harvest residue and un/under-utilized biomass availability for all 20,315 forest depletion cells is described in Alam et al.[9].

The important estimates of techno-economics parameters used in the GP model are as mentioned in Table 1.

Table 1. Estimates of parameters used in the model

Descriptions	Unit	Estimates	Remarks
Harvesting and processing costs (FHR)	CAD/gt	26	[15]
Harvesting and processing costs (UUW)	CAD/gt	31	[15]
Fixed cost due to load/unload overhead	CAD/gt	4.85	[9]
Electrical Capacity of ABTB Power plant	MWe	61	Power Plant data
Thermal Capacity of ABTB Power plant	MWth	16	Power Plant data
Electrical Capacity of ABFF Power plant	MWe	50	Power Plant data
Thermal Capacity of ABFF Power plant	MWth	61	Power Plant data
Electrical Capacity of DDPP Power plant	MWe	30	Power Plant data
Thermal Capacity of DDPP Power plant	MWth	37	Power Plant data
Electrical Capacity of AGS Power plant	MWe	23	Power Plant data
Harvesting factor*	% of BM	67	[4]
Number of forest depletion cells **	No	20,315	New estimate

Note: CAD = Canadian Dollar, BM = Biomass, gt = green tonne, yr = year
**The percentage of total biomass that can be extracted from the given area*
***1kmX1km grid of depletion cells in harvesting sites*

Descriptive statistics of biomass qualities for all 20,315 forest depletion cells, which are updated version from our previous study, are as depicted in Table 2. This helps to get the initial target levels for each of the quality goals. We select six quality characteristic related goals, namely moisture and ash contents of both forest biomass types (four goals) and thermal value of each forest biomass type (two goals) that give us a fairly good account of biomass quality information to feed into the GP model. Although estimating the values of all these parameters for the 20,315 individual forest depletion cells is a daunting task, we use [16] and Hosegood [17] to approximate the estimates of these parameters.

Table 2. Descriptive statistics of biomass quality and target levels by scenarios (n=20,315)

	Moisture content FHR (% gw basis)	Thermal value FHR (GJ/ODt)	Ash content FHR (%)	Moisture content UUW (% gw basis)	Thermal value UUW (GJ/ODt)	Ash content UUW (%)
Mean	**33.48**	**18.92**	**1.59**	**39.89**	**16.99**	**1.87**
Minimum	31.97	18.50	1.30	30.15	15.30	1.00
Maximum	39.96	20.00	3.00	55.34	18.50	2.50
Standard Deviation	2.23	0.47	0.56	9.66	1.29	0.45
Initial goals	34.00	19.00	2.00	40.00	17.00	2.00
10 % relaxation	37.40	17.10	2.20	44.00	15.30	2.20
10 % increase in efficiency	34.00	19.00	2.00	40.00	17.00	2.00
UUWAGS	No FHR for AGS only, but other plants are using it.			40.00	17.00	2.00

Note: FHR = Forest Harvest Residue, UUW = Un/under-utilized wood biomass, gw= green weight

2.2 GP model for biomass procurement

In the past, the multi-criteria decision making models, which is a common name given to all relevant models of multi-objective decision model (MODM) techniques and other related simulation models, have been applied to solve complex production and management problems in natural resources management fields including forestry [1, 18]. The goal programming model, a variant of MODM, is found to be more useful in production systems analysis because it can handle continuous problems that involve the optimisation of several simultaneous objectives. A brief sketch of GP model has been presented in [13].

The GP model is specified as minimizing the sum of positive and negative deviations from the target levels as appropriate depending upon the problem being studied. In our model, we have minimized the positive deviations of cost and heat values of FHR and UUW for each forest depletion cell and negative deviations of moisture and ash contents of two types of biomass – FHR and UUW. The formal GP model is specified as below.

Minimize $Z = p1 + \sum_{j=1}^{20315} p_{2j} + \sum_{j=1}^{20315} p_{3j} + \sum_{j=1}^{20315} n_{1j} + \sum_{j=1}^{20315} n_{2j} + \sum_{j=1}^{20315} n_{3j} + \sum_{j=1}^{20315} n_{4j}$ (1)

Subject to

$$\sum_{i=1}^{4}\sum_{j=1}^{20315}(XRES_{ij}(PRC + TC_{ij})) + \sum_{i=1}^{4}\sum_{j=1}^{20315}(XUNB_{ij}(PUC + TC_{ij})) - p1 \le C \quad (2)$$

$XRES_{ij}*(MCR_j+n_{1j})\le g_1*XRES_{ij}$ (3)

$XUNB_{ij}*(MCU_j+n_{2j})\le g_2*XUNB_{ij}$ (4)

$XRES_{ij}*(AshR_j+n_{3j})\le g_3*XRES_{ij}$ (5)

$XUNB_{ij}*(AshU_j+n_{4j})\le g_4*XUNB_{ij}$ (6)

$XRES_{ij}*(TVR_j-p_{2j})\ge g_5*XRES_{ij}$ (7)

$XUNB_{ij}*(TVU_j–p_{3j})\ge g_6*XUNB_{ij}$ (8)

$$\sum_{i=1}^{4} XRES_{ij} \le ARES_j \quad (9)$$

$$\sum_{i=1}^{4} XUNB_{ij} \le AUNB_j \quad (10)$$

$$THE_l = TCAP_i * 1000 * 350 * 24 * 3.6 \quad (11)$$

$$EE_l = ECAP_i * 1000 * 350 * 24 * 3.6 \quad (12)$$

$$TE_l = THE_i + EE_i = DB_i \quad (13)$$

$$XTB_i = \sum_{j=1}^{20315} XRES_{i,j} * (TVR_j - 0.2164 * MCR_j) + \sum_{j=1}^{20315} XUNB_{i,j} * (TVU_j - 0.2164 * MCU_j) \quad (14)$$

$$XTB_i \ge DB_i \quad (15)$$

$$XRES_{ij,} XUNB_{ij} and\ \ deviations \ge 0 \quad (16)$$

where, p_1, p_{2j} and p_{3j} are the positive deviations from the total cost target (C) thermal values target of FHR (g_5) and UUW (g_6) for each forest depletion cells, respectively;
n_{1j}, n_{2j} and n_{3j} and n_{4j} are negative deviations from target/goal levels of moisture contents of FHR (g_1) and UUW (g_2), and ash contents of FHR (g_3) and UUW (g_4) for each forest depletion cell j, respectively;
PRC is processing (harvesting and grinding/chipping) cost ($\$\cdot gt^{-1}$) of FHR at roadside;
PUC is processing (harvesting and grinding/chipping) cost ($\$\cdot gt^{-1}$) of UUW at roadside;
DB_i is annual forest biomass demand converted to energy units (GJ) of power planti ;
$ARES_j$ is annual technical availability (gt) of FHR in forest depletion cell j;
$AUNB_j$ is annual technical availability (gt) of UUW in forest depletion cell j;
$TC_{ij}$is biomass transportation cost ($\$\cdot gt^{-1}$) from the j^{th} forest depletion cell to the i^{th} power plant including loading/unloading overhead;
$XRES_{ij}$ is amount of annual FHR harvested (gt) from the j^{th} forest depletion cell for the i^{th} power plant;
$XUNB_{ij}$ is amount of annual UUW harvested (gt) from the j^{th} forest depletion cell for the i^{th} power plant;
and XTB_i is annual forest biomass converted into energy units (GJ) to be brought in the i^{th} power plant.

THE_i and EE_i are the total annual thermal and electrical energy to be produced by each plant and $TCAP_i$ and $ECAP_i$ are the thermal and electrical capacity of each plant (cf. Table 2). We assume to run the power plant for 350 days in a year and 24 hours a day. The value of 3.6 in eqns. (11, 12) is the amount of GJ energy in one kilo watt hour of power production. The parameter and equation to estimate the energy content of each type of biomass from each forest cells, which is a function of thermal value and the moisture contents (that vary among the biomass types in each depletion cells) are taken from [19].
In the above model specification, equations 11-14 are the engineering equations, which are new to this paper and that make the model more practical. Equations 2-8 are the goal constraint equations where the right hand side scalars are chosen as the goal or target, each representing the decision maker's objectives to be met with some relevant deviations by selecting the optimal choice variables $XRES_{ij}$ and $XUNB_{ij}$. The cost target is selected based on the total cost obtained from the linear programming (LP) model without putting any goal constraints with the same technical constraints, **benchmark scenario**. Different quality targets are selected based on four goal set scenarios as mentioned above. The Initial Goals scenario selects the ceiling of mean values of each of the six biomass quality characteristics as shown in Table 2. Equations (9) and (10) represent harvesting constraints, suggesting the annual harvest for each type of biomass should not exceed the available biomass in each forest depletion cell. Equation (15) constrains the total amount of energy (GJ per annum) derived from the optimal level of forest biomass harvested for i^{th} power plant should at least meet the energy production (GJ per annum) level of that plant. The general algebraic modeling system (GAMS) optimization software has been used to solve this complex problem.

2.3 Model scenario
Four different model scenarios in terms of goals sets and technical efficiency are used in order to test the various situations of multiple objectives of biomass procurement decisions for the four power plants. Before running the GP models, we ran the benchmark LP model with total cost (sum of the costs for all four plants) minimization objective with usual constraints without any quality targets (no target level set on moisture contents, thermal values and ash contents). Results of the benchmark LP model gave an idea of cost goal and results for comparisons of the biomass procurement costs for different scenarios in the GP model.
The first scenario, **Initial Goals,** includes a goal set with biomass qualities (MC and ash contents, and thermal values) having ceilings of mean values of the corresponding variables (Table 2). This scenario is set to establish a baseline goals relating to the quality of biomass, where the power plant manager may want to have higher quality feedstock as defined by these threshold goals/targets. This goal set will introduce constraints in the model as the biomass to be harvested should have MC and ash contents not more than the targets and the thermal value should be at least equal to the target. The second scenario with **10% Relaxation** deals with goal sets that relax target values for biomass qualities (the target values are as shown in Table 2) from the Initial Goals scenario by 10%. These two scenarios are run to test the sensitivity of the changes in goal levels (targets) to the costs structures of biomass procurement problems, which exemplify the importance of biomass qualities in biomass supply chains for bioenergy production. The third scenario, **10 % increase in conversion efficiency**, tests the sensitivity of costs and biomass volume to be harvested under new technological era. The fourth scenario is to use only un/under-utilized biomass for the AGS (**UUWAGS** scenario) power plant as it is planning to use UUW to produce pellets for power production in the future. Due to strict ash content requirements (<1% ash) of high quality pellets, only un/under-utilized biomass can be used for this purpose as logging residues would result in excessive bark and thus more ash content. In the last two scenarios, other quality goals remain same as in the **Initial Goals** scenario.

3. Results and discussion
First, the results obtained from the benchmark LP model scenario suggest for an optimal solution for supplying forest biomass feedstock (both FHR and UUW) from forest depletion cells in the case study area to the four power plants on an annual basis by minimizing the total annual harvesting, processing and transportation costs of biomass subject to the availability of forest biomass in each depleted forest cell. The LP model selects the optimal harvest cells for each power plant as depicted in Figure 2. From the figure we can see that Dryden CHP plant is located near the middle of the research area, and there are many forest cells closer to this power plant along with a denser network of higher class and straighter roads that imply a lower per gt procurement cost, location matters in terms of per unit biomass

procurement cost (cf. Table 3).On the other hand, Abitibi Bowater Thunder Bay CHP plant is located in the southeastern part of research area, where there is no competing power plant on its northern, eastern and southern sides in the research area. The other two power plants (ABFF and AGS) need to compete more for the forest biomass as they are located close to each other in the research area (Figure 1). Here the biomass procurement costs per gt depend on two factors, namely, location and competition as per the total volume requirements for each nearby power plants. A final note on the results of both the LP and GP models with various scenarios - this modeling approach gives the optimal network of selected forest cells to harvest both FHR and UUW biomass to meet the biomass requirements for the four power plants.

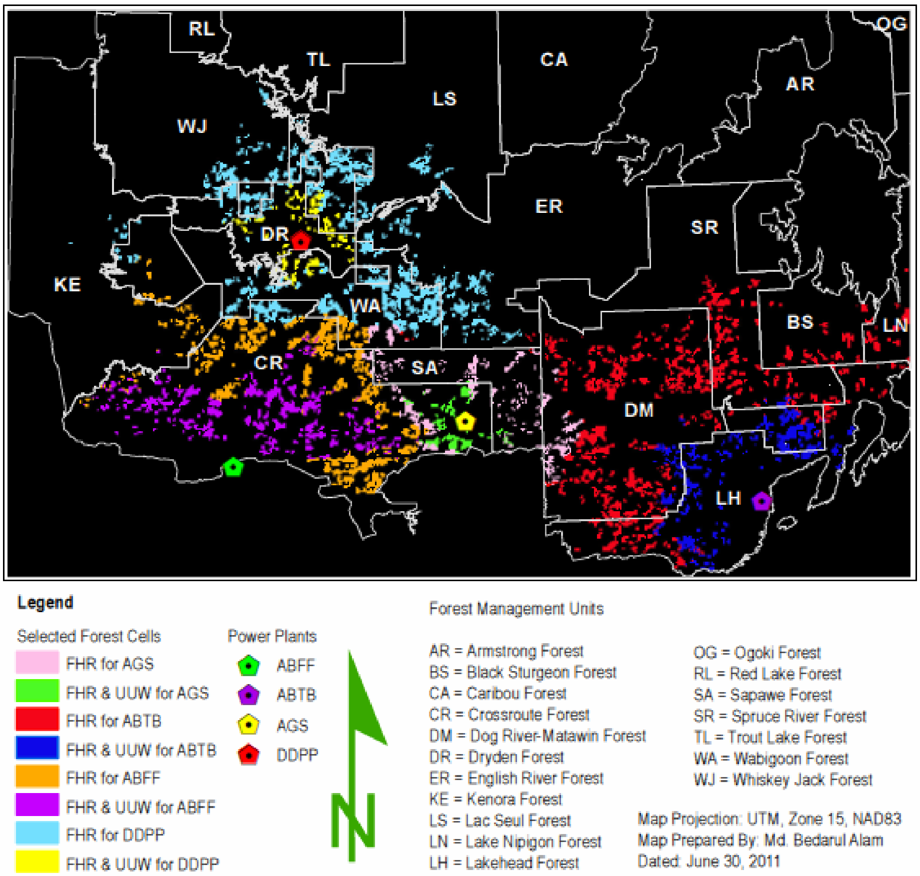

Figure 2. Optimal harvest of FHR and UUW biomass for four power plants with benchmark LP model

The models choose the most efficient forest cells out of 20,315 cells to meet the demands for all the four plants developing different networks of distribution of forest harvest cells along with the volume harvested for each scenario. We have developed a map producing application in Visual Basic, which takes the optimal cells generated by either LP or GP model as an input, and produce the visual map as shown in Figure 2. These results are very important in developing a decision support system for biomass supply chain for bioenergy productions anywhere in the world, where the similar datasets are available.

Table 3 presents the average cost estimates of per green tonne harvestin relation to various goals set and technical efficiency increase scenarios by power plants. While comparing the per gt cost in each scenario with respect to the benchmark results, we can see that per unit costs have increased significantly as we are looking for high quality biomass, thus end up paying higher per unit prices. However, the per gt costs have decreased in 10% relaxation scenario (column 3, Table 3) when compared with the Initial Goals scenario (column 3, Table 3) as this scenario allows relatively lower quality biomass than the Initial goals scenario. We can also observe that DDPP being suitably located around the dense forest areas with no nearby competing power plant has the lowest per gt cost in all scenarios. On the other hand, AGS power plant which has the lowest total volume of biomass requirement has the second least cost option to produce bioenergy, except in the UUWAGS scenario.

One interesting result to ponder is that the per gt cost for AGS in the UUWAGS scenario is significantly higher compared with other scenario because the goal of the AGS plant manager is only to procure the hardwood biomass for better quality pellet production in this case. Thus, Atikokan plant has to pay more per gt, while at the same time other competing plants have an option to grab the low cost FHR biomass previously used by AGS, thereby reducing their unit procurement costs (compare the costs with Initial Goals scenario in Table 3). These results can be useful for power plant managers to evaluate the effect of trade-offs between qualities and the costs, as well as the impacts on costs of the strategy of other competing plants. The 10% increase in conversion efficiency scenario shows the lower per gt cost as compared to the Initial goals scenario. The modeling approach developed for this study can accommodate other relevant goals or technical scenarios as well as need be to analyze the sensitivity of changing parameters on the procurement costs and forest cells network as shown in Figure 2.

Table 3. Biomass procurement costs in each scenario by power plants (CAD/gt)

Power plants	Benchmark	Initial Goals	10% Relaxation	10% increase in efficiency	UUWAGS
ABTB	38.11	41.16	38.41	40.85	41.15
ABFF	38.77	40.21	38.99	39.88	39.99
DDPP	35.74	37.57	36.00	37.34	37.54
AGS	36.13	37.46	35.96	37.21	39.11

The more important results of this improved modelling work can be observed while looking at the total volume and thereby total costs required to produce the same amount of bioenergy as discussed in our previous paper [13]. The total cost estimates are not presented here as it is obvious from the total biomass volume, which is directly proportional to the costs. Once engineering equations are introduced in the model, and with the introduction of goals constraints in the biomass qualities, we require the less total volume of biomass to produce the same amount of bioeenrgy. Table 4 summarizes the results in terms of total biomass volume required in each scenario for each power plant. We can see the drastic reduction of volume of biomass with respect to the benchmark LP scenario as we are using higher quality biomass in our GP model scenarios. The figures in the parentheses in Table 4 show the percentage reduction of total biomass requirement from the benchmark case for each power plant by model scenarios. These are important results of this study while compared with the results of [13] where total biomass volumes were kept constant for each power plant in all the model scenarios. The most drastic reduction of total biomass requirement is found in the technological improvement scenario, where about 33% reduction is observed. In rest of the scenarios, we can observe the reduction in biomass harvest in the range of 25%-27% with respect to the benchmark case.

Table 4. Total volume of biomass procurement in each scenario by power plants (gt/yr)

Power plants	Benchmark	Initial Goals	10% Relaxation	10% increase in efficiency	UUWAGS
ABTB	730,000	536,642	541,051	487,026	536,404
		(-26.49)	(-25.88)	(-33.28)	(-26.52)
ABFF	800,000	586,713	589,268	532,440	584,889
		(-26.66)	(-26.34)	(-33.45)	(-26.89)
DDPP	480,000	351,669	355,162	319,276	351,548
		(-26.74)	(-26.01)	(-33.48)	(-26.76)
AGS	200,000	147,163	148,204	133,653	149,361
		(-26.42)	(-25.90)	(-33.17)	(-25.32)

With the extension and improvement upon [13], the present GP model accounts for impacts of higher quality biomass goals and potential improvement in technology on procurement cost structures both in terms of per gt and total volume by model scenarios. By using higher quality biomass as set in GP scenario, it is found that total wood biomass harvested is reduced significantly in the bioenergy supply chains, even though the delivered per unit costs are higher. The trade-off between quality and cost has been demonstrated in this model effort, where the total biomass demand for each power plant has been endogenized through engineering process equations. The impacts of changing goals are found to be inter-dependent between plants; changing a goal in one plant affects costs at other plants.

There are many important ongoing discussions about increasing the share of renewable energy into the entire energy portfolio due to various sustainability implications in the recent past. Lund [3] brings three aspects of sustainable energy development strategy, namely, energy saving on the demand side, efficiency improvements in the supply side, and replacement of fossil-based fuels by renewable energies. Our findings can shed light on the energy efficiency scenario, and how cost-effectively renewables with biomass sources can be produced in order to fulfill the rural energy demands. This study further aids in the literature of biomass supply chain modelling with multi criteria decision-making approach by explicitly capturing the effects of biomass qualities as goals sets on the procurement costs for multiple power plants in NWO region of Ontario. This differs with the past studies in this area with similar paradigm [8, 11, 12]. Regarding technological development, we would expect an improved efficiency of CHP and power only plants with the use of higher quality biomass (as discussed in this study) in the future [20]. The trade-off between increase in conversion efficiency and the supply chain costs can be modeled by using this approach.

4. Summary and conclusions

Biomass procurement problems for four bio-energy power plants in NWO have been modelled using GP method with engineering equations and improved dataset. The approach taken in this study can greatly help in day to day operational planning problems of biomass supply chain management for bioenergy production in general. The biomass currently utilized is mainly mill and logging residues, but in future there will be a need to utilize under-utilized species and un-merchantable standing trees to meet the growing demands for biomass. All of the biomass sources have variable costs and qualities, and potential impact on other wood users (e.g., utilizing standing trees for energy would compete with other users). In this study, six quality characteristics goals, namely moisture and ash contents and thermal values of both forest biomass types are taken into account, which give a fairly good account of biomass quality information to feed into the GP model. After establishing the cost and physical quality goals characteristics we ran four different scenarios with different sets of quality goals and technological improvement situation in order to analyze the sensitivity of these scenarios on the procurement costs. The results are contrasted with the benchmark LP model, which give very good policy and operational indications for biomass supply chain management on part of the bioenergy producers.

This work represents an extension and improvement upon Upadhyay et al. [13]that helps us to find the practical real time solutions for impacts of higher quality biomass goals and potential improvement in technology on biomass procurement cost structures both in terms of per gt and total volume by model scenarios. It is found that total wood biomass harvested is reduced significantly in the bioenergy supply chains, even though the delivered per unit costs are higher. The trade-off between quality and cost has been demonstrated in this modeling effort, where the total biomass demand for each power plant has been endogenized through engineering process equations. The impacts of changing goals are found to be inter-dependent between plants; changing a goal in one plant affects costs at other plants

Conflict of interests disclosure

The authors declare that there is no conflict of interests regarding the publication of this article.

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