# A simplified logistics model for integrating BIMAT and IBSAL to estimate harvest costs, energy input, and emissions

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## ABSTRACT

The Agriculture and Agri-Food's Biomass Inventory Mapping and Analysis Tool (BIMAT) provides internet-based GIS functionality to query and visualize biomass inventory data in Canada. The Integrated Biomass Supply Analysis and Logistics (IBSAL) model is a modularized simulation of biomass supply chain. In this study, IBSAL modules are assembled to simulate harvesting of straw, stover, and switchgrass yields. The operations in this study started from combining for grain crop residues and ended in stacking bales on the field side. The equation C=aR^b Y^c was fitted to the simulated data to estimate constants a, b, and c for cost in $/dry tonne, energy input in MJ/dry tonne, and carbon emissions in kg CO2/dry tonne. Variable R is the fraction of above ground biomass removed during harvest and Y is the yield defined as biomass above ground (dry tonne/ha). These functions are supplied to the BIMAT portal and developed specific values for costs, energy input, and emissions on the map. The farm gate cost cost for the stacked bales ranged from $20 per dry tonne for high yielding regions of southwest Edmonton and Ontario to $27 per dry tonne for the eastern Ottawa region, and $31 per dry tonne for low yielding regions of central Saskatchewan. The costs are validated with published custom rates. It is recommended that the next step is to integrate IBSAL and BIMAT codes so the logistics values are generated and shown automatically on the map.

## RÉSUMÉ

L'outil cartographique d'inventaire de la biomasse [BIMAT] d'Agriculture et Agroalimentaire Canada offre des fonctionnalités internet de SIG pour rechercher et visualiser l'inventaire des données sur la biomasse au Canada. Le modèle « Integrated Biomass Analysis and Logistics » (IBSAL) [modèle intégré d'approvisionnement et de logistique de la biomasse] simule la chaîne d'approvisionnement de la biomasse en utilisant une approche par modules. Dans cette étude, les modules IBSAL sont assemblés pour calculer les coûts, les intrants énergétiques et les émissions de CO2 pour une gamme de rendements de paille, de fourrage et de panic raide. Les opérations simulées dans cette étude commençaient par le moissonnage pour obtenir les résidus de la production de grains et se terminaient par l'empilement de balles au champ. L'équation C=aR^b Y^c a été ajustée aux données pour estimer les constantes a, b, et c pour le coût en $/tonne sèche, les intrants d'énergie en MJ/tonne sèche et les émissions de carbone en kg CO2/tonne sèche. La variable R représente la fraction de la biomasse recueillie au-dessus du sol durant la récolte et Y est le rendement défini comme étant la biomasse au-dessus du sol (tonne sèche/ha). Ces fonctions sont fournies au portail de BIMAT et ont généré des valeurs spécifiques de coûts, d'intrants d'énergie et d'émissions. Les valeurs ont ensuite été enregistrées manuellement sur la carte générée par BIMAT. Le coût à la ferme (balles empilées) variait de 20 $ la tonne sèche pour les régions à haut rendement du sud-ouest d'Edmonton et de l'Ontario, à 27 $ par tonne sèche pour l'est de l'Ontario et à 31 $ par tonne sèche pour les régions à faibles rendements du centre de la Saskatchewan. Les coûts sont validés avec les taux en vigueur publiés. La prochaine étape recommandée est l'intégration des codes IBSAL et BIMAT pour que les valeurs logistiques soient générées et représentées automatiquement sur la carte.

## KEYWORDS

BIMAT, IBSAL, Biomass availability, Yield, Cost, Energy input, Emissions, Harvesting.

## MOTS CLÉS

BIMAT, IBSAL, disponibilité de la biomasse, rendement, coût, intrant énergétique, émissions, récolte.

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## INTRODUCTION

Interest in biomass has increased dramatically over the last 25 years as people seek out a renewable resource substitute for petroleum-based fuels and products while reducing the burden of GHG emissions on the environment. Developing a bio-based economy - one based on products produced by plants, animals and microorganisms - requires accurate and reliable information about the biomass feedstock supply, production and harvesting costs, and environmental impacts. Although biomass can be purpose-grown, such as switchgrass intended for ethanol production, a considerable amount of it is "opportunity" biomass, biomass that's a by-product or residue of some existing industry. Agricultural residue, straw and stover from wheat, corn and other crops, is one example; woody material left over from timber harvesting and processing, or even forest fires or pest infestations is another. Producers of bio-products need to know the types, quantities and qualities of biomass available by location to make effective use of this material. They also need to know the logistics required for harvesting, storage and transport as well as costs involved in these processes. The Biomass Inventory Mapping and Analysis Tool (BIMAT) provides internet-based GIS functionality to query and visualize biomass inventory data in Canada. Integrated Biomass Supply Analysis and Logistics (IBSAL) quantifies the logistics associated with the supply system.

The overall objective of this work is to develop simple mathematical equations to establish cost curves, energy input, and emissions as dependent variables vs. biomass yield and recovery rate as independent variables. These simple equations are developed from simulation of full scale models developed by using the Integrated Biomass Supply Analysis and Logistics (IBSAL) tool. The simple equations are suitable for integration with the BIMAT internal formulations.

## LITERATURE REVIEW

Recent advances in computational tools have made it possible to develop mathematical models for analysis and optimization of complex supply systems. Simulation methods in modeling and evaluating all the operations involved in the biomass logistics system have received the most attention (Ba et al. 2016). One of the most applicable simulation frameworks developed to represent various stages of biomass collection, processing, storage, and transport activities associated with supplying biomass to a biorefinery is Integrated Biomass Supply Analysis and Logistics (IBSAL) model. It covers a wide variety of feedstocks, harvest situations and includes an estimate of dry matter loss during several operations. IBSAL has been developed using EXTEND™ simulation platform (Sokhansanj et al. 2006b). For a detailed description of the model, see Sokhansanj et al. (2008a). IBSAL has been applied in different regions and for diverse biomass in the US and Canada, as in Sokhansanj and Fenton (2006), Kumar and Sokhansanj (2007), Stephen (2008), Stephen et al. (2010a, 2010b), Sokhansanj et al. (2008b), and Ebadian et al. (2011, 2013a, 2013b, 2018).

The Straw HAndling Model (SHAM) is another simulation model developed for designing fuel delivery systems (Nilsson, 1999a). SHAM has been presented as a dynamic simulation model for analysis of various delivery alternatives in straw handling only. This model has been used in three main regions in Sweden, Svalov, Vara, and Enkoping, as in Nilsson (1999b), Nilsson (2000) and Nilsson and Hansson (2001). The existing SHAM only enables the analysis of handling systems for straw. It does not address the issue of dry matter loss in field operations.

Several researchers have developed simulation models to optimize the costs of bioenergy chains by selecting the best harvesting and storage systems among available ones (Ba et al. 2016; US BRDB 2010). Hansen et al. (2002) developed a simulation model of sugar cane harvest and mill delivery in South Africa. Mantovani and Gibson (1992) modeled a collection system for corn stover, hay, and wood residues for ethanol production using the GASP IV simulation program. Berruto and Maier (2001) and Berruto et al. (2003) used a discrete simulation model to investigate how queue management could help improve the performance of a country elevator receiving multiple grain streams with a single unloading pit.

Although mathematical optimization modeling has been broadly used in a variety of industrial and academic fields, its application in agricultural biomass supply chain is limited. The main reason for such limited application is the high complexity and uncertainty of agricultural supply chains. For instance, modeling the weather condition as a prominent factor in the logistics system in an optimization problem would lead to a large-scale optimization model. However, several researchers have applied mathematical modeling approach for different purposes in the agricultural biomass supply chain; e.g. Cundiff et al. (1997), Tatsiopolous and Tolis (2003), Rentizelas et al. (2009a, 2009b), Nagel (2000), and Eksioglu et al. (2009).

Rentizelas et al. (2009b) have analyzed the impact of three different biomass storage methods on the total system cost. Rentizelas et al. (2009a) developed a decision support system for multi-biomass energy conversion applications. The optimization model provides the investor with answers to the following questions: 1) what is the best location to establish the biomass-to-energy facility, 2) what is the optimal relative size of the base-load combined heat and power (CHP) unit and the peak-load boiler, 3) what amount of each locally available biomass type should be used and from where should it be collected. The objective function of the optimization model is to maximize the net present value of the investment for the project's lifetime.

Nagel (2000) proposed a mixed integer linear optimization model based on the dynamic evaluation of economic efficiency which helps to find the most economical and ecological energy supply structure. The main decision variable is whether to build a heating system, a heating plant, or a co-generation plant. Eksioglu et al. (2009) proposed a mixed integer mathematical programming model which determines the most economical source of biomass, timing of harvest and storage, inventory management, biorefinery size, and biorefinery location.

Eksioglu et al. (2009) have also developed a mixed integer programming model to make both long-term decisions (supply chain design-related decisions) and

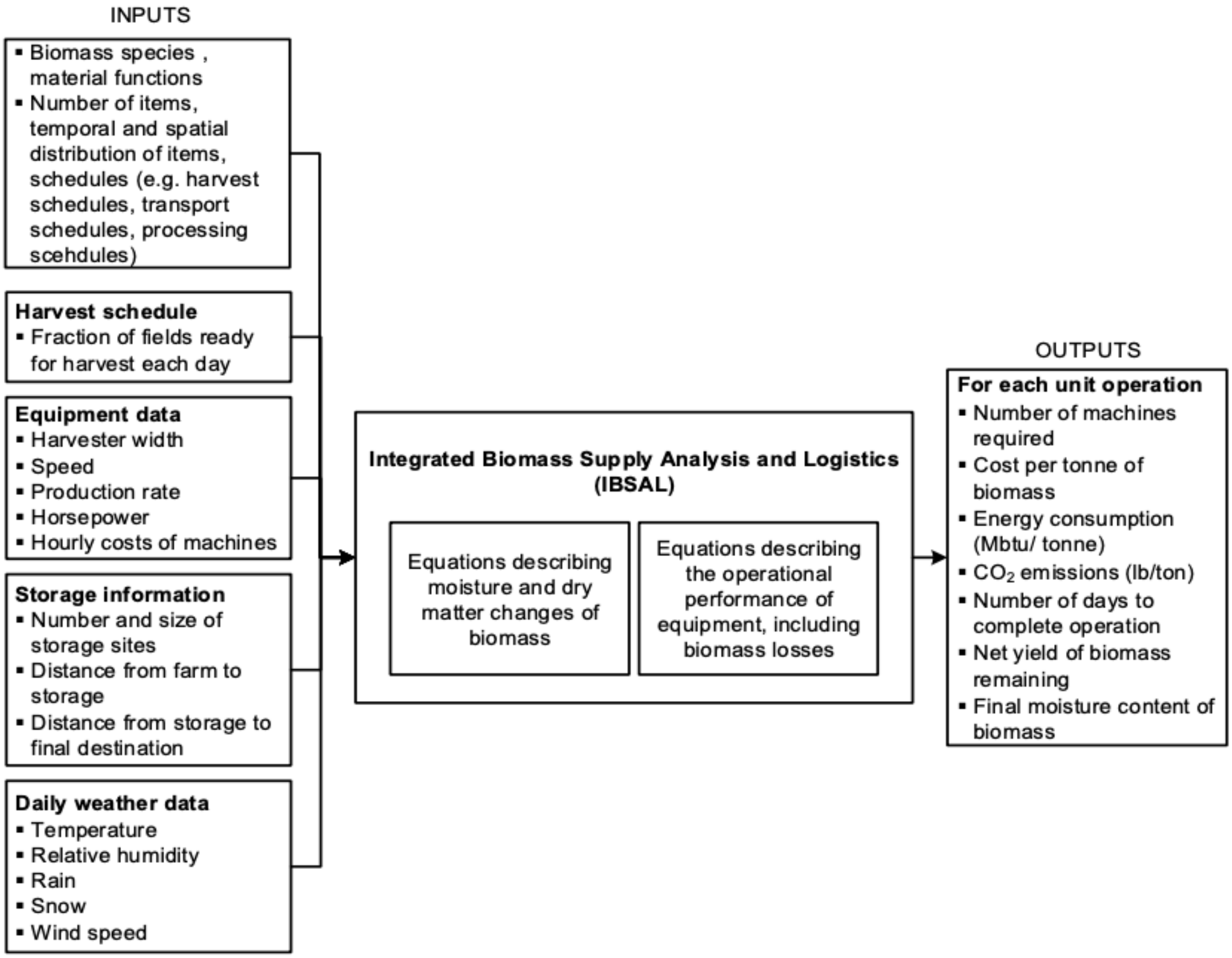


**Fig. 1. IBSAL structure.**

medium and short-term decisions (logistics management decisions). The objective of the mathematical models used in this study is to minimize the cost of delivering biofuel by coordinating long- and mid-term decisions related to the supply chain and logistics management of a biorefinery. The State of Mississippi is used as the testing ground of the proposed model.

Optimization modeling does not consider the high complexities and uncertainties inherent in biomass logistics in order to simplify the optimization models. Due to high complexity and dynamics of real-world supply chain networks, application of only one method such as simulation or optimization does not guarantee a robust supply chain network (Almeder et al. 2009). Using the combination of these methods under one framework to achieve an optimal operation plan for supply chain networks has received attention among researchers, e.g., Truong and Azadivar (2003).

To the best of the authors' knowledge, only research in the context of application of a combined optimization/simulation in the biomass logistics system is the work of Busato et al. (2005) and Ebadian et al. (2013a). Busato et al. (2005) have presented a combined approach of simulation and linear programming models to optimize the flow of biomass from field to power plant. In the first step, simulation projects the performance of a given logistics network under varying inputs such as machinery and field parameters. Once the simulation results are satisfactory, the outcomes of the simulation model are used as the input in the linear programming model. Ebadian et al. (2013a) developed an integrated optimization/simulation model. The optimization model prescribed the design of the supply area in a way that the annual biomass demand of a commercial-scale cellulosic ethanol plant is met at a minimum delivery cost for a five-year planning horizon. Given the design of the supply area, the simulation model scheduled the flow of multi-biomass in the supply chain to meet the daily biomass demand of the ethanol plant subject to the dynamics and uncertainties in the supply chain.

As discussed above, the calculation of the overall cost of delivered biomass to the biorefinery is a complex process that depends on critical factors like fluctuations in annual yields, the volumes to be shipped to the biorefinery, and incentive structures that could be available to biomass producer (Wang et al. 2017, 2018). The research reported here is limited in scope dealing with the development of

**Table 1. Typical output data from the IBSAL model to generate cost and recovery curves.**

| | Custom rates | | Energy input | | $CO_2$ emissions from equipment | | Net harvested | Biomass dry matter losses | Net yield |
|---|---|---|---|---|---|---|---|---|---|
| | (\$/t) | (\$/t) cum | (MJ/t) | (MJ/t) cum | (kg $CO_2$ /t) | (kg $CO_2$ /t) cum | (t) | (t) | (t/ha) |
| Operations Ready | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 42636 | 0 | 2.82 |
| Combine | 3.72 | 3.72 | 29.74 | 29.74 | 2.04 | 2.04 | 35748 | 7512 | 2.36 |
| Bale | 8.38 | 12.73 | 0.00 | 34.76 | 0.00 | 2.39 | 30585 | 3314 | 2.02 |
| Tractor | 9.34 | 22.07 | 103.21 | 137.98 | 7.07 | 9.46 | 30585 | 3314 | 2.02 |
| Stinger | 1.67 | 23.83 | 43.84 | 182.42 | 3.00 | 12.51 | 30453 | 141 | 0.00 |
| Loader-stacker | 1.62 | 25.55 | 23.86 | 207.08 | 1.64 | 14.20 | 30319 | 141 | 2.00 |
| Store | 4.41 | 29.96 | 0.00 | 207.08 | 0.00 | 14.20 | 30319 | 0 | 0.00 |

Cum = cumulated, t is dry tonne

simple models that can be used to integrate harvest –baling cost with BIMAT. The research did not consider complexities that would affect the cost of feedstock to biorefinery and/or the cost of biofuel.

**The IBSAL Model** The IBSAL model divides the supply chain into two activities: (1) collecting and storing the biomass at collection sites and (2) preprocessing and transporting biomass from collection sites to a biorefinery. Formulations for machinery operations and costing procedures are based on the ASABE Machinery Management Standards EP 496 and Management Data D 497 (ASABE 2006). The model is written in ExtendSim (www.imaginethatinc.com), an object oriented high-level simulation language.

The collection processes start immediately following the grain harvest or wilting of the grass in the field. The model does not include the crop budget (production costs). The model uses a machinery database to extract data on power requirements, field speed, width of the cut, and an estimation of field efficiency. The model calculates the time it takes to complete each operation. The machine time is then used to calculate equipment hourly cost, hourly energy input and hourly emissions ($CO_2$).

The model uses the specified yield data and an assumed rate of biomass recovery for each operation to calculate tonnage harvested per hour or per hectares covered. The hourly cost, energy, and emissions values are divided by the hourly tonnage or acreage to calculate \$ per tonne, MJ per tonne, and kg $CO_2$ per tonne or per ha (Figure 1). The model output includes dry matter losses due to storage and equipment operation. The logistics costs for both custom rates and ownership scenarios are reported by the IBSAL model. The number of machines can be adjusted manually to meet the quantity of biomass to be harvested and the end date for harvest operations.

Model execution is fast and it usually does not take more than 30 seconds to complete a run. The model is highly interactive; the user can modify input values and observe the resulting outputs as the program executes. A graph shows the progress of operations.

**Simulation Setup** Figure 2 shows the IBSAL set up for a typical suite of harvesting equipment. The model includes a set up module in which the parameters related to crop, size and distribution of farms, and yields are input. This module also initializes variables that are used for summing and averaging output data. Other modules outline equations representing the operation of power equipment like tractors. The data on harvest equipment are in Appendix A.

IBSAL used a Stinger type auto bale pickup and transporter for automatic loading and moving of bales to the side of the farm. Harvest of biomass, especially crop residues, follows the harvest of the main crop (grains in case of straw). These weekly data along with the average moisture content of the biomass is input to the model for the entire 52 weeks of the year. IBSAL uses daily weather data to check whether an operation can be initiated or proceed. The weather data is also used to calculate field moisture content of biomass and whether the moisture content is low

**Table 2. The IBSAL range of outputs for operations involved in this report and those rates published in Canada and in Iowa.**

| Operation | IBSAL | Custom | Reference |
|---|---|---|---|
| Combining grain (\$/ ha) | 62 - 90 | 66 - 100 | 1, 2, 3 |
| Baling (large square bales; \$/bale) | 6 - 13 | 9 - 15 | 1, 2, 3 |
| Field shredding (\$/ha) | 5 - 12 | 5 - 16 | 4 |
| Mowing conditioner (\$/ha) | 10 - 21 | 15 -20 | 1, 2, 3 |
| Bale mover (\$/bale) | 0.65 - 1.74 | 1 - 3 | 1, 4 |
| Stacking (\$/bale) | 0.63 | 0.65 | 3 |

1. Custom rate Saskatchewan: http://www.agriculture.gov.sk.ca – 2008, 2018
2. Custom rate Ontario: http://www.omafra.gov.on.ca- 2010
3. Custom rate Alberta: http: http://www1.agric.gov.ab.ca - 2009
4. Custom rate Iowa: http://www.extension.iastate.edu/publications/FM1698.pdf - 2010

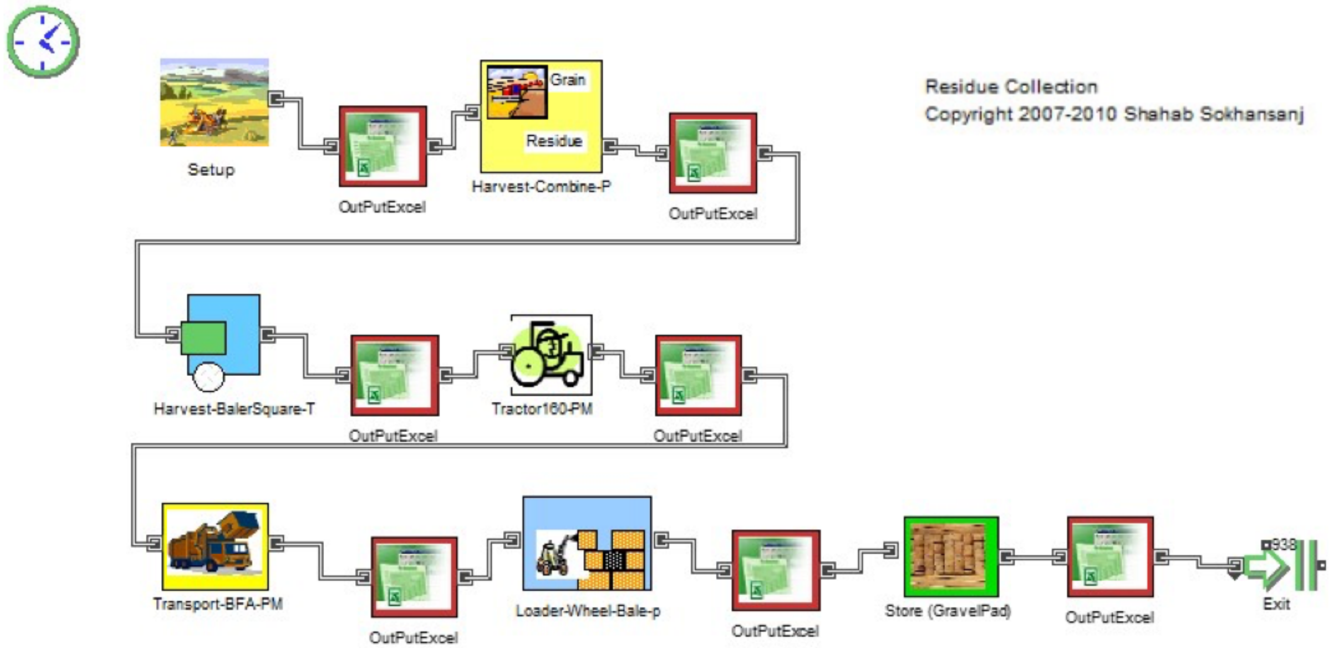


**Fig. 2. Image of IBSAL modules assembled for wheat straw harvest. The system consists of combining, baling, transporting bales to the side of the farm and stacking bales on prepared graveled ground. The bales are tarped to prevent from rain damage.**

enough for baling to take place. These data are available from Environment Canada and some from TMY2 files (Typical Meteorological Year data set, Marion and Urban 1995)

**IBSAL output** IBSAL produces an extensive output. Table 1 lists partial output that include cost of each operation and equipment, cumulative costs, energy input and $CO_2$ emissions. The output also includes dry matter loss and net yield after each operation. Values in Table 1 are the result of a single run using a single scenario. We included 10% of the cost of the combine harvester in calculating the cost of biomass. In Table 1, the cost of the combine associated with

**Table 3. Estimated coefficients for straw, stover, and switchgrass to calculate C for cost \$/tonne, energy input MJ/tonne, or emission kg CO2/tonne.**

| Crop | Parameter | a | b | c |
|---|---|---|---|---|
| Straw | Cost | 25.65 | -0.397 | -0.507 |
| | Energy input | 148 | -0.692 | -0.464 |
| | $CO_2$ emission | 10.3 | -0.665 | -0.447 |
| Stover | Cost | 52.40 | -0.679 | -0.654 |
| | Energy input | 405.0 | -0.817 | -0.740 |
| | $CO_2$ emission | 28.7 | -0.797 | -0.750 |
| Switchgrass | Cost | 33.9 | -0.000 | -0.300 |
| | Energy input | 302.4 | -0.000 | -0.460 |
| | CO2 emission | 20.73 | -0.000 | -0.460 |

$C = aR^bY^c$, a, b, and c are tabulated values,. R is rate of recovery of biomass (decimal fraction) Y is above ground yield (dry tonne/ha).

biomass harvest worked out to be \$3.30 per dry tonne. Baling involved the use of a towed large square baler and a tractor (118 kW). The cost per tonne allocation is \$7.62 for the baler and \$8.49 for the tractor pulling the baler, thus, a total of \$15.52 per dry tonne for baling.

It costs \$1.67 per dry tonne to load bales in the field, transport bales to the side of the farm, and unload bales by the side of the farm. Another \$1.47/dry tonne to stack the bales. The loading, transport and stacking is all done using a Stinger automatic bale collection system. The storage cost is \$43.13 /m$^2$ that covers the cost of preparing the ground, gravel and maintenance. Table 1 also shows the energy input to the power equipment and $CO_2$ emissions from this equipment. For the specific scenario in Table 1, the equipment consumed a total of 207.07 MJ/tonne of energy (in the form of power) and generated 14.20 kg/tonne of $CO_2$. For switchgrass, we chose a recovery fraction of around 0.90 (90% of the above ground mass is removed). The biomass yield varied from 5.68-34.09 dry tonne/ha. The sequence of equipment used for harvesting switchgrass consisted of mowing and conditioning, followed by making square bales. Baling was done when switchgrass moisture content dropped below 20%.

**Validation and model calibration** Table 2 lists published custom rates for field operations for Saskatchewan, Alberta, Ontario, and Iowa. Except in Saskatchewan, the traditional method of periodically reporting custom rates has been abandoned by other Canadian provinces. This information is now available on-line and interactive. As such, it was difficult to pinpoint the custom rates for the regions of interest. The state of Iowa and the province of

Saskatchewan reported custom rates in a pdf file that were easily accessible and usable. Iowa also included stover shredding operation that was missing from other references.

In addition to yield and fraction of biomass recovered, purchase price and the operating parameters of equipment affect the cost of the operation. Data listed in Table 2 shows that IBSAL calculated costs for combining grain, baling, field shredding, mowing, and stacking bales fall in the range of published custom rates for these operations. IBSAL calculated slightly lower costs for the field operations than the published custom rates. Custom rates include a percent to account for price fluctuations as well as a profit for the custom operator. IBSAL cost does not include these two cost items.

**Cost function** We used the linear estimation function LINEST available in EXCEL to estimate constants of the following equation,

$$C = aR^bY^c \tag{1}$$

where $C$ is cost per tonne, R is a biomass recovery rate in decimal mass fraction, and Y is the yield defined in terms of the mass of above-ground biomass in dry tonne/ha. For grain crop residue, the value of Y is calculated from multiplying the grain yield by a factor. Biomass to grain ratio for corn is 1.0 and is 1.2 for wheat (Sokhansanj et al. 2008b). To use the linear estimation function LINEST in Excel, we first took the logarithm of both sides of the equation and then used the output data for the range of recovery fractions to estimate values for constants a, b, and c. Table 3 lists the resulting constants. We also estimated the cost of harvesting stover and switchgrass. Table 3 lists these values as well. The fit of the log function of the equation to data is excellent with a coefficient of determination ($R^2$) of 0.99

**Integrating IBSAL output with BIMAT map** BIMAT provides regional maps showing the distribution and quantities of various feedstock (http://www.agr.gc.ca/atlas/bimat). This distribution can be a yield distribution (dry metric tonne per ha) or the total biomass production in a year. The public can access the program free of charge. We used the range of yields for each crop and calculated the harvest cost of the biomass using Eq. 1 and constants in Table 3. We noted that the harvest costs for harvesting and stacking at the side of the farm ranges from \$16.50 per dry tonne around Edmonton to \$33 per dry tonne for the low yielding areas of central Saskatchewan. We repeated this map for central Canada,. The harvest cost of stover ranges from \$37.40-42.90 per dry tonne for Ontario and Quebec. There is less geographic variation in average corn stover yield in central Canada than cereal on the prairies.

The machinery cost is estimated for both custom rate scenario and the ownership scenario. Custom rate is expressed in \$/hour while the ownership cost is broken into fixed cost (\$/year) and variable cost (\$/hour). Custom rate is calculated by summing the total capital cost and the operating cost, and then divided by the total assumed service life of the equipment in hours. In the ownership scenario, fixed cost is calculated in \$/year (annualized capital cost) while the variable cost is calculated in \$/hour. Fixed cost is an annual cost that includes annualized capital cost (depreciation and interest) plus other fixed costs such as machinery storage, taxes, and insurance. This cost occurs regardless of machine use. This is the number of dollars that would have to be set aside each year to just repay the value lost due to depreciation, and pay interest costs. Variable cost, in contrast, is the sum of labor, fuel and lubricants, and repairs and maintenance. This cost varies directly with the amount of use. Having both equipment custom rate and ownership scenarios gives IBSAL the capability to evaluate the purchase of the logistics equipment or contract the logistics operations out depending on the size of the biomass project.

## CONCLUSIONS

This research was initiated to demonstrate the potential for integrating the Integrated Biomass Supply Analysis & Logistics (IBSAL) with Biomass Inventory Mapping and Analysis Tool (BIMAT). IBSAL was run to simulate a number of biomass harvest to bale stacking scenarios. The operations consisted of cutting the straw (including stover and switchgrass) by using a swather/conditioner. A square baler densified the cut material into large rectangular bales. An automatic bale loader collected the bales and transported the bales to the side of the farm where the bales were stacked. Variables were yield and fraction recovered from above-ground biomass. Yield in this context referred to the biomass above the ground. IBSAL calculated cost, energy input and carbon dioxide emissions from the operation. A simple function with specific constants for each crop were developed and laid over the BIMAT resource maps. The following conclusions can be drawn.

The IBSAL calculates harvest costs that fall in the range of published custom rates. Variations in the calculated costs are due to yield and fraction biomass removed.

A simple power law equation that has cost as a dependent variable and fraction of recovered biomass and yield as independent variables has a good fit to calculated costs. The same form of equation is developed for energy input and $CO_2$ emissions.

The calculated harvest costs can be combined with the existing BIMAT yield maps to develop cost maps, energy (power) usage, and potential for $CO_2$ emissions for crop residue biomass harvest that could aid in selecting the location of a biorefinery.

**Recommendations for future research and development** This research has demonstrated that the IBSAL can be used to estimate costs, energy input, and potential emissions from equipment at the farm gate. These results should be used in conjunction with BIMAT residue maps to provide cost, energy input, and $CO_2$ emissions analysis within the BIMAT interactive map system. The logistics system evaluated in this study has a large number of small satellite storages each located at the point of production. Further IBSAL modeling is required to determine transportation costs in this system. In addition, costs of alternative satellite storage, preprocessing and transportation systems should be evaluated and combined with BIMAT production maps in order to reach the long term goal of optimizing the location of biorefineries. Allocating a percentage to the unit costs, energy input, and emissions to reflect uncertainties in prices, yields, machine availability and performance, labour, and other factors will be useful as well.


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