Analysis of five simulated straw harvest scenarios

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Sokhansanj, S., Turholow, A.F. Stephen, J., Stumborg, M., Fenton, J. and Mani, S. 2008. **Analysis of five simulated straw harvest scenarios.** Canadian Biosystems Engineering/Le génie des biosystèms au Canada **50**: 2.27–2.35. Almost 36 million tonnes (t) of cereal grains are harvested annually on more than 16 million hectares (ha) on the Canadian prairies. The net straw production varies year by year depending upon weather patterns, crop fertility, soil conservation measures, harvest method, and plant variety. The net yield of straw, after discounting for soil conservation, averages approximately 2.5 dry (d)t ha^{-1}. Efficient equipment is needed to collect and package the material as a feedstock for industrial applications. This paper investigates the costs, energy input, and emissions from power equipment used for harvesting straw. Five scenarios were investigated: (1) large square bales, (2) round bales, (3) large compacted stacks (loafs), (4) dried chops, and (5) wet chops. The baled or loafed biomass is stacked next to the farm. Dry chop is collected in a large pile and wet chop is ensiled. The baling and stacking cost was \$21.47 dt^{-1} (dry tonne), with little difference between round and large square baling. Loafing was the cheapest option at \$17.08 dt^{-1}. Dry chop and piling was \$23.90 dt^{-1} and wet chop followed by ensiling was \$59.75 dt^{-1}. A significant portion of the wet chop cost was in ensiling. Energy input and emissions were proportional to the costs for each system, except for loafing, which required more energy input than the baling systems. As a fraction of the energy content of biomass (roughly 16 GJ dt^{-1}), the energy input ranged from 1.2% for baling to 3.2% for ensiling. Emissions from the power equipment ranged from 20.3 kg CO$_2$e dt^{-1} to more than 40 kg CO$_2$e dt^{-1}. A sensitivity analysis on the effect of yield on collection costs showed that a 33% increase in yield reduced the cost by 20%. Similarly a sensitivity analysis on weather conditions showed that a 10°C cooler climate extended the harvest period by 5–10 days whereas a 10°C warmer climate shortened the harvest period by 2–3 days. **Keywords:** Biomass, harvest, collection, bale, loafer (stackers), costs, energy input, emissions, yield, prairies.

Au Canada, près de 39 millions de tonnes (t) de céréales sont récoltées annuellement sur plus de 16 millions d'hectares (ha). La production nette de paille varie d'une année à l'autre selon les conditions météorologiques, la fertilité des cultures, les mesures de conservation des sols. Les rendements moyens observés à ce chapitre s'élèvent à environ 2,5 t ha^{-1} sur une base sèche. Des techniques et équipements efficaces sont nécessaires afin de procéder au ramassage et à l'emballage de la paille pour des utilisations industrielles. Cet article s'intéresse aux coûts, aux besoins en énergie et aux émissions provenant des machines et équipements utilisés pour la récolte de la paille. Cinq scénarios ont été étudiés : (1) grosses balles carrées, (2) balles rondes, (3) amas compactés de grandes dimensions, (4) paille hachée sèche, (5) paille hachée humide. La biomasse pressée ou en amas était empilée près de la ferme. La paille hachée sèche était ramassée en un grand tas tandis la paille hachée humide était ensilée. Le coût de pressage et d'empilage était de \$21.47 ts^{-1} (tonne sèche) avec une petite différence entre les balles rondes et les grosses balles carrées. La mise en amas était l'option la moins dispendieuse à \$17.08 ts^{-1}. L'accumulation en tas de la paille hachée sèche a entraîné des coûts de \$23.90 ts^{-1} tandis que ceux de l'ensilage de paille hachée humide atteignaient 59.75 ts^{-1}. Une proportion importante des coûts de la paille hachée humide était due au procédé d'ensilage. Les besoins en énergie et les émissions étaient proportionnels aux coûts pour chacun des systèmes à l'exception de la mise en amas qui nécessitait plus d'énergie que les systèmes de pressage en balles. Exprimés en termes de fraction du contenu en énergie de la biomasse (environ 16 GJ ts^{-1}), les besoins en énergie variaient de 1,2% pour le pressage en balles à 3,2% pour l'ensilage. Les émissions provenant des machines et équipements requis variaient entre 20,3 kg CO$_2$e ts^{-1} à plus de 40 kg CO$_2$e ts^{-1}. Une analyse de sensibilité faite sur les effets du rendement sur les coûts de la récolte a montré qu'une augmentation de 33% des rendements réduisait les coûts de 20%. Une analyse de sensibilité similaire faite sur les conditions météorologiques a montré qu'un climat de 10°C plus frais allongeait la période de récolte de 5–10 jours tandis qu'un climat de 10°C plus chaud réduisait la période e récolte de 2–3 jours. **Mots clés:** biomasse, récolte, ramassage, balle, tas (pain), coûts, besoins en énergie, émissions, rendements, prairies.

INTRODUCTION

Crop residues have been collected for decades for animal feed and bedding. In most cases, the residues are baled with round or square balers, loaded in the field, and transported by truck to a storage stack adjacent to the animal requirement. Large-scale biomass collection for industrial purposes will require much larger collection amounts and radii, possibly making conventional systems uneconomic. In recent studies, it has been estimated that production returns to producers would equal \$7 to \$15 per tonne, while acquisition costs would range from \$35 to \$50, depending on distance, local demand, and systems used (Schechinger and Hettenhaus 2004). In addition to straw, chaff is also a potential low cost biomass option, representing approximately 15% by weight of the total harvested biomass. Acquisition costs represent roughly

66% of the overall feedstock cost and therefore the best opportunity for cost reduction in the agricultural crop residue needs to be investigated.

The Canadian prairies (Alberta, Saskatchewan, and Manitoba) produce more than 36 million (M) tonne of cereal grains annually, distributed over an area of approximately 16 Mha. In a high productivity year, total tonnage can reach more than 45 Mt, whereas in dry years, the tonnage may drop to 22 Mt. A minimum straw cover of 0.75 t ha^{-1} is considered adequate to prevent wind erosion when conservation tillage is used (Stumborg et al. 1996) and residues are collected 1 year in 4. The required minimum coverage can increase to 2.0 dt ha^{-1} under conventional tillage. The amount of straw that can be removed at a sustainable level has been estimated to range from 20 to 50% of the total available straw (Stumborg et al. 1996).

Cereal straw is distributed non-uniformly throughout the prairie provinces. It is estimated that on average the total straw available for utilization in Alberta is 2.6 Mdt, in Saskatchewan 4.8 Mdt and, in Manitoba 1.4 Mdt. Therefore, a maximum of 8.8 Mdt is available annually on a sustainable basis (Sokhansanj et al. 2006b). The amount of removable straw from this "available" quantity depends upon the cost of its collection and delivery.

Biomass supply logistics consist of multiple harvesting, storage, pre-processing, and transport options (Sokhansanj et al. 2002, 2006a; Kumar et al. 20007; Sokhansanj et al. 2008). A reliable supply chain must ensure that ample biomass is available for conversion; at the right time, at the right quality and specifications, at a competitive cost, and with minimum health risks to workers and the environment (Jenkins and Sumner 1986). Logistics of straw supply on the prairies are characterized by large collection areas, time and weather-sensitive crop maturity, a short window for straw collection, and competition from concurrent harvest operations. An optimized collection, storage and transport network ensures timely supply of biomass with minimum costs.

Objectives

The objectives of this paper are: (1) to apply a dynamic simulation approach to analyse several options for harvest of cereal straws on the prairies, and (2) to study the effect of climate conditions on progress of harvest and the logistics of gathering and stacking straw.

The study includes estimation of the biomass yield, harvest costs, energy input, and estimation of carbon dioxide (CO_2) emissions from power equipment used for the harvest operations. A sensitivity analysis of costs and harvest logistics to changes in yield and weather patterns concludes the study.

METHOD

A dynamic simulation biomass supply model (IBSAL) has been developed to represent various stages of biomass collection, processing, storage, and transport activities associated with supplying biomass to a biorefinery. The supply model has been developed using EXTEND™ simulation platform (Sokhansanj et al. 2006b). The model simulates the effects of climate, geographical, and biological factors on the cost of delivering biomass from single or multiple sources. It can minimize the cost of delivered biomass by identifying an optimum mix of biomass sources, machinery, handling processes, capacities, storage, transportation systems, and pre-processing options. Additional information that can be obtained from the model includes: energy input-output relations, labour demands, effects of feedstock quality requirements on costs, emissions (carbon equivalent), and delays due to shortage of machines and labour. It also identifies potential bottlenecks and implications of various storage options. For a detailed description of the model, see Sokhansanj et al. (2008).

The biomass collection and supply system is divided into two activities: (1) collecting and storing the biomass, and (2) transporting the material from the storage site(s) to the biorefinery. The time between the completion of grain harvest for a 64 ha (160 acre) unit of production and the collection of straw depends upon the storage strategy. For dry storage, collection must wait until the straw reaches a safe moisture content before it can be baled. For wet storage or silage, there is no need to wait for drying; the collection process can start immediately following grain harvest. In most situations involving wet storage, the biomass is not baled, it is collected using a forage harvester. These options will be discussed in detail in the analysis section.

Collection site

For the collection analysis we used a quarter section of land roughly 64 ha (exactly 160 acre, i.e., a quarter of a square field 1 mile × 1 mile) as a production unit. The IBSAL model is a discrete event model, meaning that each item is uniquely tracked throughout the entire supply chain. The item in our discrete event modelling, a 64 ha production unit satisfies this modelling requirement. Inputs included production unit size, yield, distance that the material has to travel from the field to the road side (coordinates of the travel distance ranged from 0.16 km to 1 km), and the winding factor, which represents the deviation from a straight line for travel. We assumed 1.2 for the winding factor.

Safe storage moisture content depends upon temperature. Blunk et al. (2003) found that rice straw bales harvested near Sacramento, California, showed signs of spontaneous heating when moisture exceeded 20%. We used 20% moisture content as a safe moisture level for baling on the Canadian prairies. This value is used in order to delay baling in the field until the biomass moisture content is 20% or lower. We also assumed that the farm operations stop at temperatures below $-20°C$ until the weather becomes warmer. Any of the input values can be varied and their effect on the biomass cost and other outputs can be investigated using the simulation program.

Estimating straw yield

At present, straw yield is not measured, and all we have are the grain yield data. The straw yield (dt ha^{-1}) is estimated from the straw-to-grain ratio (SGR). The large variation in SGR among various published data has been attributed to tillage, residue management, N application, climate (Linden et al. 2000), and plant maturity stage at harvest. Pordesimo et al. (2004a, 2004b) measured the above-ground fractions of corn (*Zea mays* L.) before and after harvest in test plots in Tennessee. The SGR reached a maximum value of 0.86 on day 104 after planting, when grain moisture content was 41% wet basis (wb). The SGR decreased to 0.68 by day 143, when the grain moisture content was 13% (wb).

Seecharan et al. (2002) reported a SGR range of 0.83 to 1.33 for dryland wheat (on the Canadian prairies), dependent upon the soil type. The low SGR was on Brown soils and the high SGR was on Black soils. The trend in SGR for barley was similar, and varied from 0.63 on Brown soils to 0.94 on Black soils. To estimate straw availability in Idaho, Patterson et al. (1995) quoted the SGR values ranging from 1.33 to 1.88 for winter wheat and from 1.17 to 1.67 for spring wheat. The low values were for dry land and the high values were for irrigated wheat. Nelson (2002) used an SGR of 1.7 for winter wheat and 1.3 for spring wheat.

Stumborg et al. (1996) showed that the estimates of the SGR depended upon the type of combine used to partition grain from biomass. On dark brown soils, the chaff fraction of the straw harvested using a rotary combine was 0.25, and for a conventional combine it was 0.15. The SGR also was strongly related to the combine settings, especially the height of the cut. Summers et al. (2003) and Igathinathane et al. (2006) showed that SGR values depend upon the portion of the straw considered in calculating SGR. For rice, 40% of biomass was in internodes, 43% in leaves, 4% in nodes, and 3% in panicles (Summers et al. 2003). For corn stover, the bottom 40 cm stalk sections had 66% of total dry matter mass (Igathinathane et al. 2004). Such data are not available for small grains.

PAMI (2001) found that in Saskatchewan, the overall average straw to grain ratio was 1.1:1.0. A SGR of 0.8 excluding stubble and chaff suggests a harvestable SGR of 0.88. Rotary combines that are becoming popular on the Canadian prairies do not leave much straw behind. It is safe to use a factor of 0.80 as SGR for this study.

Table 1 lists maximum, minimum and average straw yields based on grain yield and SGR (Sokhansanj et al. 2006b). Not all of the straw produced can be removed. The amount of surface residues required for erosion control varies depending upon soil texture and field slope. Coarse-textured (sandy) soils require relatively large quantities of residue for control of wind erosion. The amount of residues required to control water erosion increases with field slope (Campbell et al. 2002).

Campbell and Coxworth (1999) recommended retaining an average of 1300 kg ha^{-1} crop residues on all soils to minimize erosion. Kline (2000) recommended 30 to 50% of the straw be left on the soil to effectively protect the soil from wind and water erosion. Lindstrom et al. (1979) used 50 to 75% of available straw to protect soil from wind and water erosion. Also, there is a nutrient management requirement that should be included; hence, the 1 year in 4 removal limit for straw applies to the frequency of biomass removal on the prairies. Given the current farming practices, an average of 1000 kg dry straw per ha was assumed a reasonable biomass to be left on the land for soil conservation (Stumborg et al. 1996).

The available yield was calculated by subtracting 1 dt ha^{-1} from the straw yields listed in Table 1. The average

Table 1. Range of straw yield (t ha^{-1}) before* and after deductions made for soil conservation.**

		Alberta		Saskatchewan		Manitoba		Prairies overall	
Crop		Before	After	Before	After	Before	After	Before	After
Wheat	Avg.	2.86	1.86	2.15	1.15	2.05	1.05	2.36	1.36
	Max.	3.24	2.24	2.61	1.61	3.19	2.19	3.01	2.01
	Min.	2.05	1.05	1.54	0.54	0.70	0.00	1.43	0.53
Barley	Avg.	2.46	1.46	2.06	1.06	1.94	0.94	2.15	1.15
	Max.	2.84	1.84	2.43	1.43	2.96	1.96	2.74	1.74
	Min.	1.82	0.82	1.42	0.42	0.70	0.00	1.32	0.42
Oat	Avg.	2.63	1.63	2.47	1.47	2.34	1.34	2.48	1.48
	Max.	2.88	1.88	2.92	1.92	3.10	2.10	2.96	1.96
	Min.	2.16	1.16	1.93	0.93	1.03	0.03	1.71	0.71
Flax	Avg.	1.75	0.75	1.42	0.42	1.12	0.12	1.43	0.43
	Max.	1.88	0.88	1.70	0.70	2.03	1.03	1.87	0.87
	Min.	1.62	0.62	1.16	0.16	0.37	0.00	1.05	0.26
Straw overall	Avg.	2.81	1.81	2.09	1.09	1.92	0.92	2.27	1.27
	Max.	3.18	2.18	2.49	1.49	2.91	1.91	2.86	1.86
	Min.	2.13	1.13	1.55	0.55	0.72	0.00	1.47	0.64

*Straw to grain ratios: wheat 1.1, barley 0.8, oats 1.1, flax 1.2.
**Average 1 t ha^{-1} for soil conservation.

gross yield for straw across the prairies was 3.24 dt ha^{-1}. The average net yield dropped to 2.24 t ha^{-1} after discounting for 1 dt ha^{-1} for soil conservation. For most regions, the net straw yield was approximately 2 dt ha^{-1}, but in some cases it dropped below 1 dt ha^{-1}. In the case of flax, the 1 dt ha^{-1} deduction for soil conservation may not be applicable because flax residue left in the field can interfere with subsequent tillage operations. Farmers usually chop the flax straw during combining, bale the straw for removal, or bunch the straw and burn the piles in the field.

Harvest and collection timelines

The commencement of grain harvest depends upon local climate conditions and kernel moisture content. Farmers prefer to complete harvest as quickly as possible to preserve crop yield and quality and to have time for preparing the land for the next crop. Harvest operations may continue until cold, rainy, or snowy conditions make field operations difficult. For northern prairie areas (black and grey-wooded soil zones), harvest begins roughly the second week of August and lasts until the end of September and rarely extended to mid October. More than 80% of the crop is often harvested by the first week of September. Cool, rainy conditions in the northern areas slow the harvest in the middle of September, but usually the return of warm, dry conditions by the end of the month allows the harvest to continue. Harvest operations end for the most part by the second week of October.

The collection of straw starts immediately after the first field is harvested for grain. The progress of the straw collection depends on the amount of equipment deployed, the grain harvest system used, and local weather patterns. For the IBSAL model, we assumed that each millimetre of rain postpones going to the field by 1 hour, and every millimetre of snow postpones going to the field by 2 hours. These delays apply to traffic only. The delays owing to the moisture content of the plant caused by the absorption and desorption processes are calculated in the model. We also stipulated that at temperatures below −20°C the collection operations will remain inactive until warmer temperatures return. Other factors that influenced the progress of the harvest consisted of a minimum moisture content for the biomass to be baled for safe storage. This critical value was set at 20% (wb).

In the Edmonton region, early harvest starts around August 10. Fig. 1 shows the progress of harvest in Alberta for 1000 production units (each unit = 64 ha). The number of production units increases rapidly to almost 45 per day. The number drops to 1 and eventually zero after almost 60 days. The progress of straw harvest follows the same trend as the progress of grain harvest. In our model we selected the number and size of equipment that would have allowed the collection operations to be completed within 90–110 days after the start of grain harvest. In other words, biomass harvest lasted 30 days after the completion of the grain harvest. The model requires initial moisture content of biomass associated with each production unit. We assumed 14% wet basis during the entire harvest season.

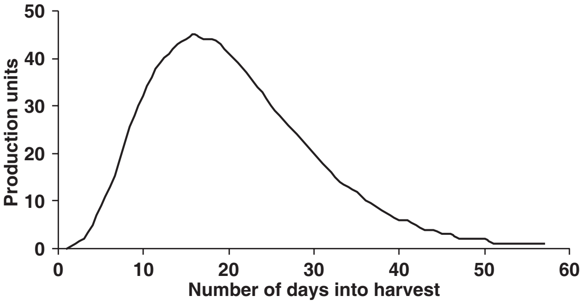

Fig. 1. Cereal harvest progress in Alberta. Day zero (0) corresponds to August 1.

Climatic data

The weather information is extracted from the Canadian Climate Normals 1971–2003, Environmental Canada website (Environment Canada 2007). The data are converted to daily average dry bulb temperature (°C), daily snow fall (mm), daily average relative humidity (decimal), daily evaporation (mm), and daily rainfall (mm). Daily evaporation was calculated using a pan evaporation formula that requires temperature, relative humidity and daily average wind speed (Sokhansanj et al. 2006a). Temperatures during the harvest season steadily decrease, making straw collection more difficult. Rain or snow is a barrier to the progress of harvest. For example, a 10 mm rainfall or snowfall delayed a field operation by 10 or 20 h, respectively.

Collection options

Biomass collection activities commence immediately after the grain is harvested. The conventional method of collecting straw is to bale it and store it on the side of the field. Other methods of collecting straw, such as use of a loafer (stacker) or forage harvester, may be possible. In this work we studied five collection options (Fig. 2). We assume a sequence of operations in the following analysis. This does not mean that every field or location follows the same sequence. Presentation of a particular sequence of operation and related equipment in the following section is to demonstrate the utility of the IBSAL model.

Option 1 – Square bale. For this option, the straw is raked into windrows immediately after the grain is combined. The rake gathers dispersed straw into a narrow windrow. If the straw is wet, it is left in the field until its moisture content reaches a safe level (usually less than 14%). A baler picks up the straw and forms large rectangular bales 1.2 m × 1.2 m × 2.4 m (4 ft × 4 ft × 8 ft). The bales are left in the field. At a later date, or as convenient, an automatic bale collector travels through the field and collects eight bales, carries the collected bales to the side of the field, and unloads the bales into a stack. The stacks are tarped using a lift truck.

Option 2 – Round bale. Round baling is similar to square baling, except a round baler picks up the biomass and forms it into 1.8 m diameter × 1.5 m wide (6 ft × 5 ft) bales. In this system, a towed bale wagon with self-loading

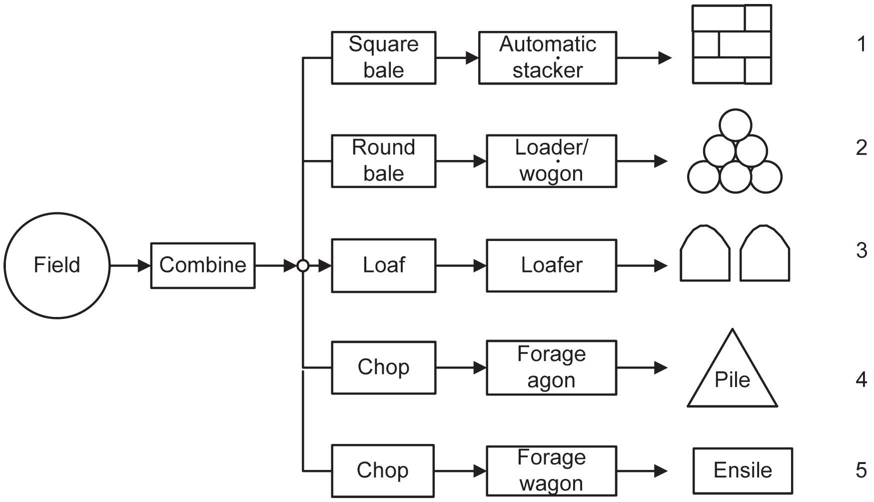

Fig. 2. Flow diagram of straw harvest options analyzed in this paper.

mechanism loads bales onto the deck of the bale wagon. The bale wagon is towed to the side of the road where a front-end bale loader picks up the bales and places them in the stack. The bales are then tarped.

Option 3 – Loaf. Loafing (stacking) of forages became popular in the 1960s and early 1970s with the development of intensive dairy operations. The system has declined in popularity with the advent of compact and more productive round balers. A loafer (or stacker) picks up the biomass from a windrow and forms the biomass into a large stack, about 2.2 m wide, 6.1 m long and 3.1 m high (8 ft wide, 20 ft long, 10 ft high). The roof of the stacker (loafer) acts as a press, pushing the material down to increase the density of biomass loaf. The loafer transports the biomass to the side of the field and unloads the stacked biomass. The stack gets the dome shape of the stacker roof, and thus easily sheds water. A tarp is not needed for a loaf.

Option 4 – Dry chop. In this system a forage harvester picks up the dry biomass from windrow, chops it into smaller pieces (25 to 50 mm), the chopped biomass is blown into a forage wagon travelling along side the forage harvester. Once filled, the forage wagon is pulled to the side of the field and unloaded. A piler (inclined belt conveyor) piles the material in the form of a large cone.

Option 5 – Wet chop. In this system a self-propelled forage harvester picks up the dry or wet biomass from the windrow. The chopped biomass is blown into a forage wagon that travels along side of the harvester. Once filled, the wagon is pulled to a silage pit where the biomass is compacted to produce silage. We modeled a concrete pit 18 m wide, 36 m long, and 4 m high. A loader pushes the biomass into the pit.

Equipment and costs

Table 2 lists the field equipment used for collection and transportation of biomass. The choice of size and operating conditions are based on: (1) the latest model of equipment commercially available for agricultural production, (2) the typical operational performance data as given by the ASABE (2007a, 2007b), (3) the opinions of custom operators and farmers, and (4) the personal experience of the authors.

Rates and prices vary and those used represent a typical situation as of June 2007. The interest rate was assumed 6%. Machinery prices, especially tractors, vary plus or minus 20% depending on the options and equipment used. We assumed all tractors to be four-wheel units, equipped with a cab. Other assumptions included the number of annual working hours, the service life of equipment, field and road speeds, and field efficiencies. ASAE EP 496.3 (ASABE 2007a), and ASAE D497.5 (ASABE 2007b) contain these pertinent data.

Table 2 lists custom rates calculated using the engineering economic analysis as described above [for detailed method see Sokhansanj and Turhollow (2002)]. Custom rates in Table 2 represent the sum of fixed and variable costs. The hourly rate includes the power equipment attached to the implement. For example, balers, rakes, loafer/stackers, shredders, and wagons need a power source to power and tow the implement. In addition to hourly costs, Table 2 lists equipment specifications and operating conditions.

RESULTS and DISCUSSION

A viable supply chain must ensure that ample biomass is available for conversion at the right time, at the right quality and specifications, at a competitive cost, and with minimum health risks to workers and the environment. Our goal was to determine equipment requirements in order to complete all field operations within 90-110 days of the start of harvest. The transport of biomass (straw) to a biorefinery would take place from field stacks gradually over the entire year.

Straw Collection Analysis

We prepared inputs to the IBSAL model for straw collection using weather data for Edmonton, Alberta. Five options were considered: square baling, round baling,

Table 2. Specification of equipment used in modelling the collection and transport.

Equipment	Power (kW)	Volume (m^3)	Speed* (km h^{-1})	Eff.	Unload time (min)	Bulk density (kg m^{-3})	Custom rate (\$ h^{-1})
Baler round (1.5 m wide × 1.8 diameter)	90	3.82	8.0	0.65	–	160	62.34
Baler square (4 m × 4 m × 8 m)	120	3.45	8.0	0.80	–	192	93.26
Forage harvester (SP)	210	–	5.5	0.70	–	–	95.91
Front end loader (silage compactor)	90	2.04	–	0.70	0.50	–	47.97
Loafer (2.4 m wide × 3.1 m high × 6.2 m long)	120	45.38	6	0.65	5.00	112	68.94
Rake	60	–	10	0.80	–	–	37.91
Automatic bale loader and stacker (SP) – 8 bales	15	–	15	0.90	0.25	192	126.48
Bale wagon (towed) – 17 bales	60	–	10	0.85	0.25	160	72.60
Forage wagon (2.4 m wide, 3.1 m high, 6.2 m long)	90	45.38	10	0.90	2.00	4	49.46
Piler (20 t h^{-1})	30	–	–	0.90	–	–	35.76
Concrete silo pit with walls (18 m wide × 4 m high × 36 m long)	–	2,592	–	–	–	320	4758.00**

*Per year.
**Working with for all field machinery is assumed 4.3 m (14 ft).

loafing, chopping dry, and chopping wet. Table 3 lists the results of these runs using an average straw yield of 2.04 dt ha^{-1} (0.9 dt acre^{-1}). The number of pieces of each type of equipment (in parentheses) for each option was determined by trial and error, with the objective of completing the collection and storage of the biomass within 90–110 days of the harvest start date. Table 3 lists the dry tonnage per unit (64 ha)$^{-1}$ for each operation. For example, with option 1 the initial tonnage per 64 ha was 142.1 dt. The net yield dropped to 141.4 dt (64 ha)$^{-1}$ by the last operation. This loss of biomass was due to either physical losses during harvest (i.e., shattering) or losses due to chemical decomposition of the biomass (dry matter losses). The model assigns physical losses to raking and baling operations, and chemical decompositions to biomass in the queue (in field or in storage).

Table 3 lists three important outputs for each operation on a dry tonne basis: costs in \$ dt^{-1}, energy spent on that operation in MJ dt^{-1}, and carbon dioxide emitted from burning fossil fuels in powering equipment in CO_2 kg dt^{-1}. Carbon was converted to carbon dioxide (CO_2) using a molecular weight ratio ($CO_2/C = 44/12 = 3.67$). It is possible to further refine the GHG inventory to include emission levels of other gases (e.g., methane from anaerobic breakdown), but these calculations and analyses are beyond the scope of this paper.

A rake was used for baling and loafing. Dry and wet forage harvesting were used without the use of a rake. The cost of raking (\$3.62 dt^{-1}) can be added to this operation. Square baling was slightly higher in cost (\$12.42 dt^{-1}) than round baling (\$11.77 dt^{-1}). The cost of roadside delivery was similar, though two different methods of collecting, transporting and stacking were used. The cost of tarping was \$2.24–2.74 dt^{-1}. The total cost in \$ dt^{-1} represents the cost over the final tonnage. It is not the sum of individual costs (\$ dt^{-1}) for each operation, as the tonnage varies from one operation to next due to dry matter loss. Loaf cost includes picking up the straw transporting it to the side of the farm and unloading.

The most expensive option was wet storage because of the high cost of a concrete silo pit (\$59.75 dt^{-1}). The least expensive was loafing (\$17.08 dt^{-1}) due to fewer pieces of equipment and operational requirements than baling. Next to wet storage, dry pile was the most expensive operation (\$23.90 t^{-1}) due to the high cost of forage harvesters. Square baling and round baling systems had similar costs, of approximately \$21.00 dt^{-1}. These costs did not include payment to the farmer, which could be around \$10.00 dt^{-1}. Payment to the farmer covers the cost of residue prior to collecting it from field. The cost covers a fertilizer value for the straw. The cost does not include any of the production or harvest operations.

Energy input and emissions were strongly correlated with collection costs, except for loafing, which required more energy input (319.4 MJ dt^{-1}) than baling operations; 258.7 and 290.1 MJ dt^{-1} for square and round baling, respectively. The two largest energy inputs were those for dry (467.1 MJ dt^{-1}) and for wet (522.8 MJ dt^{-1}) chop. As a fraction of the energy content of biomass (roughly 16 GJ dt^{-1}), the energy input ranged from 1.2% for baling to 3.2% for ensiling. Emissions generated from the power equipment ranged from 20.3 kg CO_2 dt^{-1} to more than 40 kg CO_2 dt^{-1}.

Sensitivity of collection costs to yield

Several factors affect the cost and availability of biomass. These include yield and weather elements. Fig. 3 shows the effect yield levels of 1.36 dt ha^{-1} (low yield), 2.04 dt ha^{-1} (base case yield), and 2.74 dt ha^{-1} (high yield) have on the

Table 3. Costs, energy input, and carbon dioxide emissions for five options of biomass collection (number of equipment used to complete harvest is in the parenthesis).

Collection options	Operation	dt (64 ha)$^{-1}$	\$ dt^{-1}	Energy (MJ dt^{-1})	CO$_2$ (kg dt^{-1})
Option 1. Square bale and stack using one step load 8 bale and stack and stack	Rake (20)	142.3	3.62	62.3	4.840
	Bale square (21)	141.4	12.42	168.4	13.090
	Road side and stack (15)	141.4	3.03	14.0	1.100
	Tarp (2)	141.4	2.24	13.9	1.082
	Total		21.47	258.7	20.295
Option 2. Round bale load on wagon with 17 bales and stack using a loader	Rake (25)	142.8	3.62	62.4	4.950
	Bale Round (35)	142.0	11.77	175.7	13.750
	Transport to roadside (10)	142.0	2.31	20.3	1.650
	Stack (3)	142.0	0.77	14.5	1.100
	Tarp (2)	142.0	2.74	14.6	1.100
	Total		21.38	290.1	22.550
Option 3. Loaf and stack	Rake (20)	142.3	3.62	62.3	4.767
	Loaf and stack (23)	141.3	13.29	253.8	19.800
	Total		17.08	319.4	24.750
Option 4. Dry chop and pile	Forage harvest dry (20)	141.6	20.24	418.7	32.633
	Transport to roadside (30)	141.6	1.60	27.6	2.145
	Pile (4)	141.5	1.71	15.8	1.228
	Total		23.90	467.1	36.483
Option 5. Wet chop and silage	Forage harvest wet (20)	141.7	23.41	473.3	36.850
	Transport to roadside (30)	141.7	1.60	27.5	2.200
	Ensile (1)	141.6	32.33	14.2	1.100
	Total		59.75	522.8	40.700

delivered cost of straw biomass. A high or low yield represents a change in yield of ±33%, which is a reasonable variance for the study area. As the yield increased, the cost of biomass delivered decreased and vice versa. The increase was generally 16% for dry pile and almost 48% for the wet pile. Similarly, the decrease in cost as a result of a 33% increase in yield was 13% for round bales and 24% for the wet chop. More material was collected per unit time when the yield increased. We did not decrease the speed of a piece of field equipment in response to a change in biomass yield. In practice however, operators adjust the forward speed of equipment to compensate for an increase or decrease in yield so the net mass of the collected material remains the same. This analysis will be expanded in future publications.

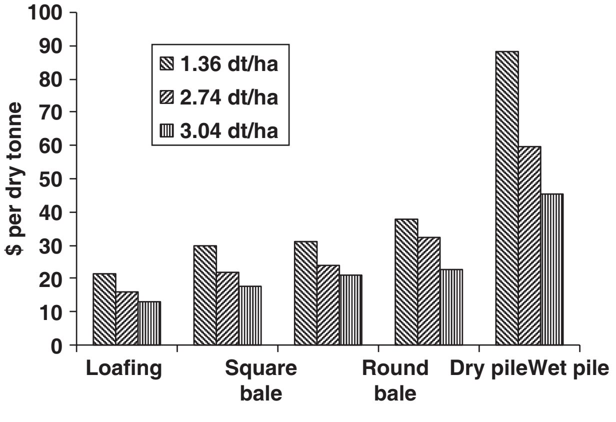

Fig. 3. Collection cost sensitivity to the yield of straw. The delivered cost in \$ t^{-1} for three straw yields of 1.3, 2.74, 3.04 dt ha^{-1} are shown.

Sensitivity of harvest time frame to weather

For this analysis, we constructed two weather scenarios from the normal weather data for Edmonton: (1) a warm weather situation in which the average daily temperature during harvest was 10°C above normal. The precipitation for rainy days was reduced by 1 mm; (2) a cool weather situation where the average daily temperature was reduced by 10°C. The precipitation for rainy days was increased by 1 mm. New evaporation rates were calculated for both cool and warm weather conditions using the modified temperatures. The IBSAL model was run with all three weather data cases: normal, warm, and cool.

We used a yield of 2.04 t ha^{-1} as the base case. The number of pieces of equipment to complete stacking of the biomass within 91-92 days (base case) was determined by trial and error. Table 4 shows the number of days required to complete harvest varied from 88.5 days for a warm dry year to 95.9 days for a cool rainy year. The collected biomass was square-bale for these case studies. The number of days for dry or wet chop using a forage harvester increased from 90 days for a warm year to more than 109 days in a cool year. This 10-20 day difference in the harvest window may have an impact on removing the straw from the field before the cold and snow halt operations, but generally farmers can wait until warm

Table 4. Sensitivity of the completion date to weather conditions.

	Number of days after the start of harvest		
Collection option	Normal weather	Warm weather	Cool weather
Square bale	91.1	88.5	95.9
Round bale	91.9	89.7	99.4
Loaf	91.3	91.2	95.2
Dry chop	92.1	90.2	109.5
Wet chop	92.2	90.2	109.5

periods prevail to get back on the field and complete the work.

On-farm observations

The normal on-farm system for straw in the prairies is round baling behind a combine (without raking), and stacking the bales either in the field or in some selected stacking area. Field stacks are usually single-tier, and the intent is to have them removed prior to fall or spring work. Yard stacks may be several tiers high. Usually the straw is neither covered nor shredded, and some spoilage is expected. Twine often breaks on the bottom tiers if they are moved in the winter.

Most straw is harvested by the users of the straw. There are few custom operators available in Canada, reportedly due to the low financial returns. Also, there are issues of contamination that may happen as a result of equipment moving from one field to another. (incidental cross contamination due to dispersing weed seeds and various stages of insects). Producers planning to use their own straw will have equipment to do their own baling, stacking, and transporting. Producers buying straw usually buy in the immediate vicinity and use their own harvesting equipment. Custom work that does take place is usually by other producers, or producers charging the straw buyers for services provided. The typical rates are as follows: shredding (if mowing is needed for example when a high stubble left standing) \$25 ha^{-1}, baling \$8 bale^{-1}; e.g., stacking \$1.5 bale^{-1}; load and haul on the farm \$2.5 bale^{-1}; and load and haul to a storage site \$4 to \$5 bale^{-1}.

CONCLUSIONS

The model outputs for each operation were cost, energy input, and CO_2 emissions. The baling and stacking costs were \$21.47 dt^{-1} with little difference between round and large square baling. Loafing was the least expensive option at \$17.08 dt^{-1}. Dry chop and piling was \$23.90 dt^{-1}, whereas wet chop and silage was \$59.75 dt^{-1}. Much of the wet chop cost was in ensiling. Energy input and emissions strongly correlated with the costs (i.e., the more expensive options had higher emissions), except for loafing, which required more energy input than the baling systems. As a fraction of the energy content of biomass (roughly 16 GJ dt^{-1}), the energy input ranged from 1.2% for baling to 3.2% for ensiling. Emissions from the collection equipment ranged from 20.3 kg CO_2 dt^{-1} to more than 40 kg dt^{-1}. A sensitivity analysis on the effect of yield on collection costs showed that increasing yield by 33% reduced the collection cost by about 20%. An average 10°C cooler temperature during harvest season increased the number of required days to complete harvest and collection by 5–10 days. An average 10°C warmer temperature during harvest season decreased the number of required days to complete harvest by 2–3 days.

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REFERENCES

ASABE. 2007a. Standards. ASAE EP496.3 FEB2006, *Agricultural Machinery Management*, 356–361. St. Joseph, MI: ASABE.

ASABE. 2007b. Standards. ASAE D497.5 FEB2006, *Agricultural Machinery Management Data*, 362–369. St. Joseph, MI: ASABE.

Blunk, S.L., M.W. Yore, M.D. Summers, G.K. Lau, S.T. Tang and B.M. Jenkins. 2003. *Quality and Property Changes in Rice Straw During Long Term Storage*. ASAE paper number 036091. St. Joseph, MI: ASABE.

Campbell, C.A. and E. Coxworth. 1999. *Feasibility of Sequestering Carbon Through Use of Crop Residue for Industrial Products*. Report prepared for the Agriculture Round Table, Ottawa, ON: Agriculture and Agri-Food Canada.

Campbell, C.A., R.P. Zentner, S. Gameda, B. Blomert and D.D. Wall. 2002. Production of annual crops on the Canadian Prairies: trends during 1976-1998. *Canadian Journal of Soil Science* 82: 45–57.

Environment Canada. 2007. The *National Climate Data and Information Archive*. http://www.climate.weatheroffice.ec.gc.ca (2007/02/01).

Igathinathane, C., A.R. Womac, S. Sokhansanj and L.O. Pordesimo. 2006. Mass and moisture distribution in above ground components of standing corn plant. *Transactions of the ASAE* 49: 97–106.

Jenkins, B.M. and H.R. Sumner. 1986. Harvesting and handling agricultural residues for energy. *Transactions of the ASAE* 29: 824–836.

Kline, R. 2000. Estimating crop residue cover for soil erosion control. Soil fact sheet, Order no. 641-220-1. Abbotsford, BC: Resource Management Branch, Ministry of Agriculture and Food. htp://www.agf.gov.bc.ca/resmgmt/publist/600series/641220-1.pdf (2004/10/15).

Kumar, A. and S. Sokhansanj. 2007. Switchgrass (*Panicum vigratum* L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. *Bioresource Technology* 98: 1033–1044.

Linden D.R., C.E. Clapp and D.H. Dowdy. 2000. Long range corn grain and stover yields as a function of tillage and residue removal in east central Minnesota. *Soil and Tillage Research* 56: 167–174.

Lindstrom, M., E. Skidmore, S. Gupta and C. Onstad. 1979. Soil conservation limitations on removal of crop residues for energy production. *Journal of Environmental Quality* 8: 533–537.

Nelson, R.G. 2002. Resource assessment and removal analysis for corn stover and straw in the eastern and Midwestern United States – rainfall and wind induced soil erosion methodology. *Biomass & Bioenergy* 22: 349–363.

PAMI. 2001. Reliable Data on Sustainable Wheat Straw Availability – Straw Production. Final report. Project number 500E. Humboldt, SK: PAMI.

Patterson, P., L. Makus, P. Mamont and L. Robertson. 1995. *The Availability, Alternative Uses and Value of Straw in Idaho*. Report prepared for Idaho Wheat Commission Project BD-k251. Idaho Falls, ID: College of Agriculture, University of Idaho.

Pordesimo, L.O., S. Sokhansanj and W.C. Eden. 2004a. Moisture and yield of corn stover fractions before and after grain maturity. *Transactions of the ASAE* 47: 1597–1603.

Pordesimo, L. O., W. C. Edens and S. Sokhansanj. 2004b. Distribution of aboveground biomass in corn stover. *Biomass & Bioenergy* 26: 337–343.

Schechinger, T.M. and J. Hettenhaus. 2004. Corn stover harvesting: grower, custom operator, and processor issues and answers. Technical Memorandum ORNL/SUB-04-45000008274-01. US Department of Energy. Washington, DC. 98 pp.

Seecharan, R., R. Gill, S.N. Kulshreshtha, B. Jenkins and O. Bussler. 2002. Expanded use of biofuels: economic and greenhouse gas emissions related implications for the agricultural sector. *World Resource Review* 14: 204–222.

Sokhansanj, S. and A.F. Turhollow. 2002. Baseline cost for corn stover collection. *Applied Engineering in Agriculture* 18: 38–43.

Sokhansanj, S., A.F. Turhollow, J. Cushman and J. Cundiff. 2002. Engineering aspects of collecting corn stover for bioenergy. *Biomass & Bioenergy* 23: 347–355.

Sokhansanj S., A. Kumar and A.F. Turhollow. 2006a. Development and implementation of integrated biomass supply analysis and logistics (IBSAL) model. *Biomass & Bioenergy* 30: 838–847.

Sokhansanj, S., S. Mani, M. Stumborg, R. Samson and J. Fenton 2006b. Production and distribution of cereal straw on the Canadian Prairies. *Canadian Biosystems Engineering* 48: 3.39–3.46.

Sokhansanj, S., A.F. Turhollow and E.G. Wilkerson. 2008. Development of the Integrated Biomass Supply Analysis and Logistics Model (IBSAL). Technical Memorandum ORNL/TM-2006/57. Oak Ridge, TN: Oak Ridge National Laboratory.

Stumborg, M., M. Townley Smith and E. Coxworth. 1996. Sustainability and economics issues for cereal crop residue export. *Canadian Journal of Plant Science* 76: 669–673.

Summers, M.D., B.M. Jenkins, P.R. Hyde, J.F. Williams, R.G. Mitters, S.C. Scardacci and M.W. Hair. 2003. Biomass production and allocation in rice with implications for harvesting and utilization. *Biomass & Bioenergy* 24: 163–173.