BIOMASS AND BIOENERGY 32 (2008) 603–612

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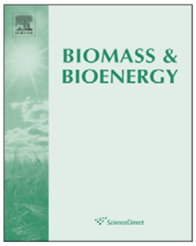

The economics of harvesting and transporting corn stover for conversion to fuel ethanol: A case study for Minnesota

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ARTICLE INFO

Article history:
Received 6 March 2006
Received in revised form
12 December 2007
Accepted 17 December 2007
Available online 31 January 2008

Keywords:
Biomass
Feedstock
Lignocellulose
Monte Carlo
Zea mays

ABSTRACT

Corn-stover feedstock costs were estimated for a proposed biomass-to-ethanol conversion facility in southern Minnesota, USA, accounting for county-specific yields and transportation distances, erosion constraints, machinery specifications, and transportation, storage, and densification costs. Monte Carlo simulation was used to estimate the probability distribution of costs under alternative assumptions on key parameters whose values vary widely in the literature. For a facility producing 0.189 $\mathrm{hm^3\,y^{-1}}$ of ethanol, marginal feedstock cost was estimated at \$60 $\mathrm{Mg^{-1}}$ (\$200 $\mathrm{m^{-3}}$ ethanol) for the more-intensive harvest method and \$72 $\mathrm{Mg^{-1}}$ (\$210 $\mathrm{m^{-3}}$) for the less-intensive method. Costs were greater than \$68 $\mathrm{Mg^{-1}}$ (\$240 $\mathrm{m^{-3}}$) for a facility producing $>$ 0.757 $\mathrm{hm^3\,y^{-1}}$ ethanol under the more-intensive method, and greater than \$93 $\mathrm{Mg^{-1}}$ (\$320 $\mathrm{m^{-3}}$) for the less-intensive method. Monte Carlo simulation estimated a mean marginal cost of \$57 $\mathrm{Mg^{-1}}$ (\$69 $\mathrm{Mg^{-3}}$ under the less-intensive harvest method) for 0.189 $\mathrm{hm^3}$ ethanol output, with a \$12 (\$10) standard deviation. Costs were found to be at or below \$68 $\mathrm{Mg^{-1}}$ 90 percent of the time (\$78 $\mathrm{Mg^{-1}}$ for the less-intensive method). A \$12 $\mathrm{Mg^{-1}}$ standard deviation in stover cost would result in a \$40 $\mathrm{m^{-3}}$ swing in ethanol cost.

1. Introduction

The recent spike in oil prices and a preoccupation with energy security have resulted in widespread efforts to secure new domestic sources of energy in the United States. These sources include, but are not limited to, corn ethanol, diesel derived from soybean oil and other fats, and wind, solar, and hydrogen energy. All of these, with the exception of hydrogen energy, are being produced at the commercial scale, albeit in relatively small quantities. Another potential source being studied is biomass. Biomass is defined as any plant or plant-derived material, and includes anything from corn stover and forest residue to animal manure and urban waste. Due to its relative abundance, corn stover (cobs, stalks, and leaves) is of particular interest. It is estimated that the United States currently produces 68 $\mathrm{Tg\,y^{-1}}$ (dry) of corn stover; by comparison, the second-most abundant agricultural source of biomass is manure, at 32 $\mathrm{Tg\,y^{-1}}$ (dry) [1].

The objective of this work is to derive corn-stover feedstock cost estimates for a proposed biomass-to-ethanol facility located in a feedstock-abundant region in midwestern USA. Previous work has attempted to estimate such costs, but, in general, do not adequately account for variations in yield and transportation distance, storage, and feedstock densification, key variables in determining the economic feasibility of stover as a fuel feedstock. For example, Gallager et al. [2] estimated costs of corn-stover collection and transport using the same cost parameters for all counties and crops, but did not allow yields and nutrient-replacement costs to vary across counties. Perlack and Turhollow [3] presented a thorough analysis of machinery costs specific to corn stover, but assumed a homogenous corn yield, stover yield, and corn

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doi:10.1016/j.biombioe.2007.12.012

acreage density for a $3.6 \times 10^4\,km^2$ collection area. Sokhansanj and Turhollow [4] assumed a single corn yield, stover yield, and transportation distance in their work. Sayler and Von Bargen [5] focused on a specific facility location and specific counties in Nebraska, adjusting for erosion constraints using county-level data, and present a detailed account of field operations, but made simplifying assumptions on stover yields. Graham et al. [6] developed a GIS-based cost-estimation model, but they focused on switchgrass, not corn stover, and when the model was used for corn-stover collection in [7], no details were provided as to how the estimates were derived.

In contrast to the works cited above, [8,9] detailed actual stover collection projects, recounting experiences of stover collection in Iowa and Wisconsin, and Indiana, respectively.

The method employed by this work falls in between that of the two aforementioned groups of studies. Like the latter group, this study presents estimates for collecting and transporting corn stover for delivery to an actual location; like the former group, however, the estimates presented here are hypothetical, not the results of an actual collection event. Consequently, and in contrast to previous work, this study derives estimates based on actual historic yields and actual transportation distances for each county in the study region. Furthermore, using county-specific data from [10], residue availability in each county is adjusted for water and wind erosion constraints such that erosion does not exceed USDA-established tolerable soil loss levels. Also, we test the sensitivity of our results using Monte Carlo simulation on the most uncertain (and contentious) parameters: corn yields, stover moisture content, stover collection efficiency, and farmer participation rate. Finally, because our primary interest was in the potential of corn stover to be converted into fuel ethanol, in addition to reporting quantities and costs in feedstock terms (Mg and $\$\,Mg^{-1}$), this work reports volume and cost estimates in ethanol terms (m^3 and $\$\,m^{-3}$).

2. Data and methods

A case study was carried out for a proposed corn-stover-to-ethanol facility located in Martin County, Minnesota, USA (43.68 N, 94.56 W). Martin County is located in the heart of the corn-producing region of Minnesota and northern Iowa, has access to state and interstate highways and railroads, and is crossed by major gas and liquid pipelines. It was assumed that this facility would be able to draw stover supplies from all Minnesota and border counties in Iowa, South Dakota, and Wisconsin with average annual corn production of at least 210 Gg (see Fig. 1). The resulting study area covered a total of

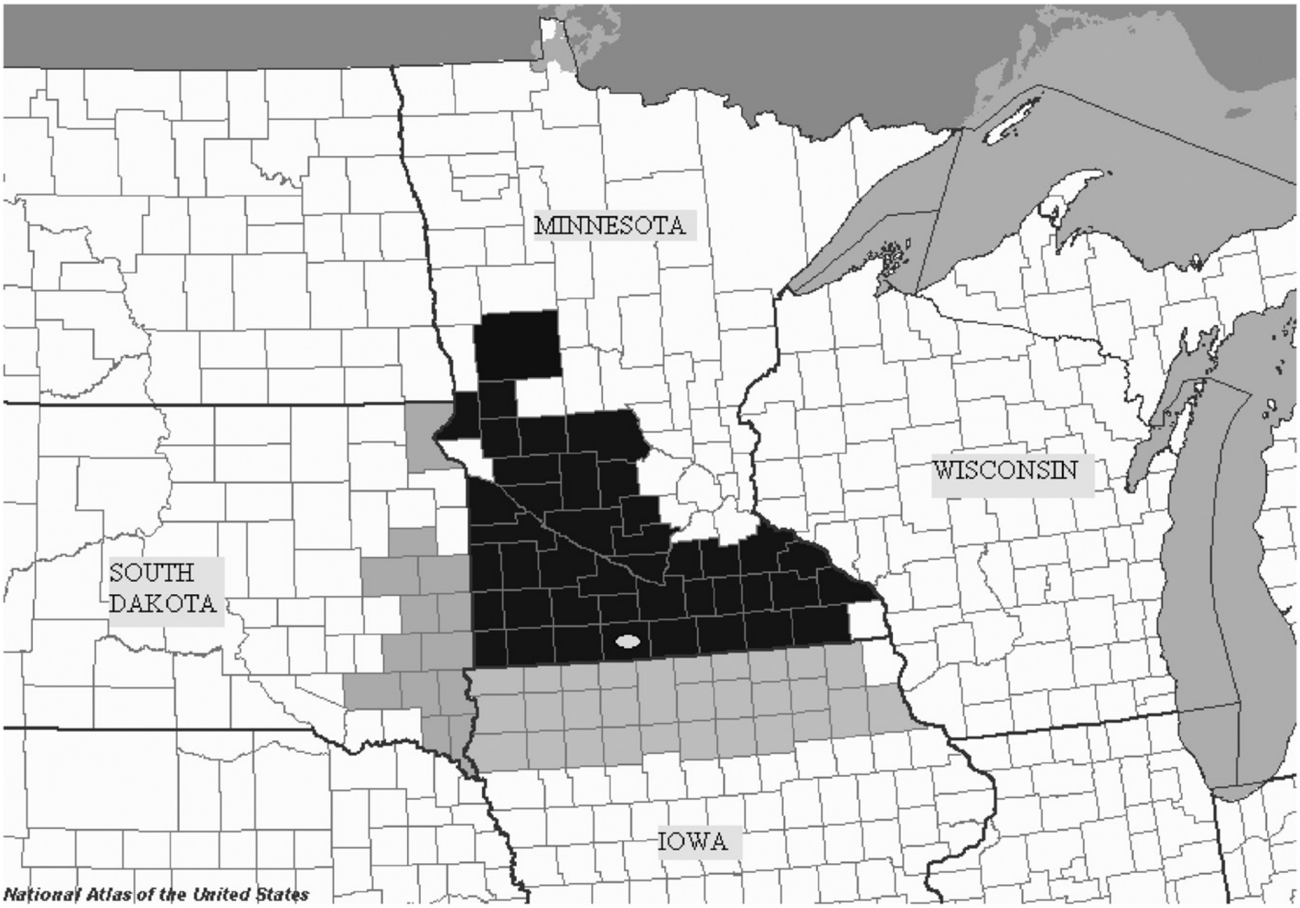

Fig. 1 – Study area considered for corn-stover harvest. The oval denotes conversion facility location. (Map template courtesy of National Atlas of the United States [33].)

140 Mm^2; none of the Wisconsin border counties met the production threshold.

2.1. Estimate of stover quantities

Table 1 contains the values for parameters assumed throughout the analysis. Area harvested and corn yields were obtained from [11] for the years 2000–2004. Bone-dry weight of a bushel of corn grain was assumed to be 21.3 kg [12]. Quantities of stover necessary to remain in the field for two tillage regimes, current and no-till, was taken from [10], which account for wind and water erosion only, and were estimated such that erosion is kept at or below tolerable soil-loss levels. See [13] for a detailed discussion of the methods used to estimate these quantities. It was assumed that 50 percent of the region's harvestable area was available, referred to hereafter as the farmer participation rate, and was tested for sensitivity later in the analysis.

2.2. Stover collection operations

Two collection methods were constructed for this paper. The first method assumed that the spreader on the combine would be turned off such that the stalks would be deposited in a windrow behind the combine. The windrows would then be baled using a large round baler. It was assumed that this method collects 30 percent of total stover produced. The second method assumed that the combine spreader would be on and scatter the plant material going through the combine. A stalk shredder would then shred the stalks, and a rake would be used to windrow the stalks. Stover would then be baled using a large rectangular baler. It was assumed that this method collects 40 percent of total stover. The assumptions on collection efficiency were tested for sensitivity later in the analysis.

Table 2 contains the set of operations, machinery, and cost information for the two collection operations. A round baler pulled by a tractor was assumed to be used that would produce 1.4 m wide × 1.6 m diameter bales weighing 335 kg (dry) (assuming 144 $\mathrm{kg\,m^{-3}}$ density). Additionally, it was assumed that bales would be wrapped in plastic mesh rather than twine to reduce losses during transportation and for better water shedding during storage. Once the stover was baled, it was assumed that an automated bale picker (with a capacity of 14 round bales) pulled by a tractor would collect the bales from the field and transport them to the field edge to be loaded on semi trailers. A telehandler with a bale hugger attachment was assumed to be used to transfer bales from the picker to the semi-trailer.

For the rectangular-bale method, it was assumed that a 6 m stalk shredder pulled by a tractor would make the first pass over the spread stover, followed by a twin rake pulled by a tractor to form the windrows. A large rectangular baler pulled by a tractor would then be used to bale the windrows, producing bales 2.4 m high × 1.2 m wide × 0.9 m long, weighing 609 kg (dry) (assuming a density of 224 $\mathrm{kg\,m^{-3}}$). This baler was chosen because, although it does not produce the largest square bales, it produces a bale size that maximizes the available semi-trailer weight capacity. Rectangular bales were assumed to be held together with twine. Bales were then assumed to be collected and moved to the field edge using a

Table 1 – Base-case parameters used for stover collection and transport analysis, for round- and square-bale methods

General		
Crop yield year	2000–04 Avg.	
Stover-to-grain dry-weight ratio	1:1	
Corn grain bushel bone-dry weight (kg)	21.3	
Farmer participation rate (%)	50	
Stover to ethanol conversion rate (undenatured $\mathrm{m^3\,Mg^{-1}}$)	0.292	
Plant online time (h)	8406	
Collection	*Round*	*Square*
Stover collection efficiency (%)	30	40
Bale size (dia. × w/l × w × h) (m)	1.4 × 1.6	2.4 × 1.2 × 0.9
Dry bale density (dry) ($\mathrm{kg\,m^{-3}}$)	144	224
Dry bale weight (kg)	335	609
Bale moisture content (%)	16	
Actual bale weight (kg)	399	725
Bales picked by bale picker per hour	42	24
Bales moved by telehandler per hour	48	
Transport		
Maximum semi-cargo load (Mg)	20.9	
Semi-trailer usable cargo space dimensions (m)	2.7 × 2.7 × 14.6	
Bales per semi-load	27	28
Cargo weight per semi-load (Mg)	10.78	20.29
$\$\,\mathrm{km^{-1}}$ loaded (semi-hauled) (0–40 km)	1.75	
$\$\,\mathrm{km^{-1}}$ loaded (semi-hauled) (41–161 km)	1.38	
$\$\,\mathrm{km^{-1}}$ loaded (semi-hauled) ($>$161 km)	1.23	
Unloading/stacking cost at plant ($\$\,\mathrm{bale^{-1}}$)	1.15	
Storage		
Number of days direct hauled	21	
Storage losses (%)	2	
Number of rectangular bales stacked high	6	
Number of round bales stacked high	5	
Storage site size (ha)	4.1	
Land costs ($\$\,\mathrm{ha^{-1}\,y^{-1}}$)	40	
Land prep ($\$\,\mathrm{ha^{-1}}$)	12,141	
Equipment cost (telescopic handler) ($\$\,\mathrm{bale^{-1}}$)	1.15	
Building cost ($\$\,\mathrm{m^{-2}}$)	0.35	
Building/land-prep life (years)	20	
Densification		
Densified stover bulk density ($\mathrm{kg\,m^{-3}}$)	625	
Densified stover moisture content (%)	10	
Densification cost ($\$\,\mathrm{Mg^{-1}}$ (dry))	25.72	
Cargo weight per semi load (Mg)	20.9	

Table 2 – Estimated machine operating costs for collecting corn stover

	kW	List 2005 (k$)	Purchase (k$)	$h\,y^{-1}$	$\$\,h^{-1}$	$\$\,ha^{-1}$	$\$\,bale^{-1}$	$\$\,Mg^{-1}$	Source
Round-bale method									
97 kW MFWD Tractor	97	8.00	79.20	500					[13]
45 kW Tractor	45	25.20	22.68	500					[13]
JD 557 Round Baler	45	21.31	19.18	250	54.27	26.71			[14]
Megatooth Pickup			0.90						[14]
High-moisture kit			0.30						[14]
Surface Wrap			2.90						[14]
Bale Wrap (3 times)				250			1.70	4.26	[8]
Inland 2500 Bale Mover	97	20.78	18.70	250	70.99		1.69	4.23	[15]
Deere 3220 Telehandler	85	75.43	67.89	500	55.00		1.15	2.87	[16]
Deere Frontier Bale Hugger			1.00						None
Square-bale method									
97 kW MFWD Tractor	97	88.00	79.20	500					[13]
45 kW Tractor	45	25.20	22.68	500					[13]
Stalk Shredder 6 m	97	19.22	17.30	250	60.65	19.32			[13]
JD 705 Twin Rake	45	13.21	11.89	250	32.54	10.38			[16]
Hesston 4790 Rectangular Baler	97	82.09	73.88	250	98.40	23.87			[14]
Knotter cleaner			1.60	250					[14]
Bale Twine				250			0.72	0.99	[8]
Inland 4000 Bale Mover	97	31.80	28.62	250	65.50		2.73	3.77	[15]
Deere 3220 Telehandler	85	75.43	67.89	500	55.00		1.15	1.58	[16]
Deere Frontier Bale Squeezer			1.00						None

bale picker (with a capacity of eight rectangular bales). A telehandler fitted with a bale squeezer would then be used to transfer the bales to a semi-trailer.

Tractor and stalk shredder purchase prices were taken from [14]; baler and baler-attachment price data were taken from [15]; bale-wrap and twine costs were taken from [8]; bale-picker prices were obtained from [16]; rake and telehandler prices were taken from [17]. All per-hour machinery costs were estimated using Lazarus and Selley's machinery cost spreadsheet [14], as were the per-hectare costs of the stalk shredder, rake, and balers. Purchase price was assumed to be 90 percent of the list price. It was assumed that tractors and telehandlers were used 500 h annually and all other machinery was used 250 h annually.

Per-bale costs of bale wrap and twine were taken directly from [8]. Per-bale costs for the bale pickers were calculated from the per-hour cost assuming that the picker made three loads per hour (i.e., 3 × 14 round bales per hour and 3 × 8 square bales per hour). Per-bale cost for the telehandler was calculated from the per-hour cost using the assumption that 48 bales could be transferred per hour [4]. The remaining per-bale and per-hectare costs were specific to each county because they depended on the quantity of stover available per hectare. Costs per Mg were a direct conversion from per-bale costs.

2.3. *Nutrient replacement*

When corn stover is left in the field, plant nutrients contained therein eventually make their way into the soil as the residue decomposes. Thus, when the stover is harvested those nutrients are removed with it, and hence unavailable to the subsequent year's crop. Therefore, a potential cost to the farmer is that of replacing these nutrients with the use of artificial fertilizers in order to maintain crop production levels. The crop nutrients of interest are nitrogen, phosphorus, and potassium. However, because in this analysis soybeans follow corn, nitrogen does not need to be replaced. The average replacement rate reported in [8,12,18] is 3.1 kg of phosphate and 16.5 kg of potash per Mg of stover removed. United States Department of Agriculture-Economic Research Service [19] reports 2000–2004 average phosphate ("superphosphate") and potash (potassium chloride) fertilizer prices of \$0.05 and \$0.04 kg^{-1}, respectively, resulting in an average nutrient replacement cost of \$4.64 Mg^{-1} of stover removed.

2.4. *Transportation*

Distance from each supply county was based on distance from the county seat to plant location, and was taken from [20] for Minnesota counties and from [21] for all others. There are several issues to consider for transportation and storage, and a detailed discussion of them is given in [22]. Here, it was assumed that all baled stover would be staged at the field edge then transported to storage by semi-trucks to regional storage sites. Distance from storage to conversion facility was assumed to be equal to the distance from county seat to Fairmont, MN. The decision to use flatbed semis was based on the fact that most farms would be able to supply stover sufficient to fill a semi-truck load, and because semis carry larger loads, the number of trips can be reduced substantially. It was assumed that the maximum cargo load for semis was 20.9 Mg [23]. However, this maximum may not necessarily be achieved. It was assumed that the semi-trailer has 2.7 m × 2.7 m × 14.6 m of cargo space, bales have a 16-percent moisture content, and that the dry density of round and square bales is 144 and 224 kg m^{-3}, respectively. The trailer dimensions would thus allow for 3 high × 2 wide × 6 long = 36 square bales; however, such a load would exceed the weight limit of 20.9 Mg. Thus, 27 square bales could be loaded for a total weight of 20.3 Mg. For round bales, the trailer dimensions would allow for two bottom rows and one top row of nine bales each, for a total of 27 bales. This load would weigh only 10.8 Mg. The cost per loaded km was assumed to be $1.75 for loads within 40 km of the plant, $1.38 for loads between 41 and 161 km, and $1.23 for loads traveling greater than 161 km [24]. Finally, it was assumed that the cost of unloading and stacking bales at the storage site was equal to the cost of using the telescopic handler for similar purposes on farm: $3.42 and $1.88 Mg^{-1} for round bales and square bales, respectively.

2.5. *Storage*

The window for harvesting corn stover in the study region is about 21 days, running from about the middle of October to the beginning of November [25]. Consequently, a good deal of storage is needed to supply a plant processing only corn stover throughout the year. The storage site would require good drainage and either a gravel or concrete base for ease of equipment use and vehicle traffic [8]. To accommodate equipment and vehicle traffic (driveways, etc.), as well as necessary spacing between bale stacks, it was assumed that the total area necessary for the storage site would be twice that of the space required for the bales themselves. Round bales are assumed to be wrapped in plastic, and therefore, can be stored outdoors. Rectangular bales, however, are not wrapped, and would require indoor storage. Rectangular bales were assumed to be stacked 6 high, and round bales were assumed to be stacked in pyramids of 50 (12 bales long, 5 high). A storage-loss factor of 2 percent was assumed for both bale regimes. Land rent was assumed to be $40 ha^{-1}, and land preparation cost, $12,141 ha^{-1}. Building cost (for square bales only), was found to range between $0.14 and $0.56 m^{-2} [26,27]; an average building cost of $0.35 m^{2} was assumed here. The site was assumed to depreciate over 20 years, and debt servicing and overhead was assumed to be 15 percent of building cost annually [27]. Equipment cost (telescopic handler) was estimated to be $1.15 bale^{-1}. In total, storage costs were estimated at $14.26 Mg^{-1} for square bales and $7.52 Mg^{-1} for round bales. Although costs are higher for square bales, the total land area needed for storage is about half that of round bales.

2.6. *Bale densification*

Bale densification has the potential to significantly reduce transportation and storage costs, and to improve material handling and processing, leading, perhaps, to additional cost reductions. Some work has been done by Mani et al. [28] and Sokhansanj et al. [29] to establish cost estimates for densification processes. These results were incorporated here to estimate costs of including a densification step in the present system. Mani et al. [28] reported significant reductions in costs for larger densification plant sizes relative to smaller ones. Consequently, this report adopted their cost estimates for a facility processing 68 Gg y^{-1} of feedstock, which was the second-largest facility size reported, with a densification cost of $25.72 Mg^{-1}.

Densification increases stover density to 625 kg m^{-3} (bulk density). It was assumed that a densification facility would be located at each regional storage site, so that no additional hauling cost would be incurred. Because the stover must be hauled to the storage-densification site as bales, there is no opportunity for transportation cost savings for this segment. Furthermore, because bales would arrive at the plant at a rate exceeding those processed, stover would be stored as bales, not as densified stover, and thus storage costs would be identical to that of the non-densified stover regimes. Additionally, it was assumed that the demand from the conversion facility would be such that the densified stover would need to be immediately hauled to the conversion facility; therefore, no long-term on-site stover storage would be required. Regarding transportation cost to the conversion facility, there are substantial gains made relative to hauling round bales, as densification doubles the load weight, reducing per-Mg transportation cost by half. For rectangular bales, however, the cost reduction is small, as a load of rectangular bales is nearly at capacity already, and there is thus little room to take advantage of the substantial increase in density. Results assuming densification are reported along with those for baled stover.

3. Base-case results

With regard to erosion, it was found that under current tillage practices, erosion constraints limited the quantity of stover that could be collected in counties along the Mississippi River, some in northern Minnesota, Plymouth County in northwestern Iowa, and all of the South Dakota study counties. Under no-till, erosion was a limiting factor during just one of the 5 years of yield data for only a handful of counties in Minnesota, Iowa, and South Dakota. Thus, erosion constraints effectively eliminated the South Dakota counties as sources of stover under current tillage practices. However, erosion was not a limiting factor in any of the major corn-producing counties in the study, which lie primarily in southern Minnesota and northern Iowa.

Table 3 contains the estimated marginal cost and transport distance of delivered stover as well as the total harvest area necessary to supply corn stover for ethanol output of 0.095, 0.189, 0.379, 0.568, and 0.757 hm^{3} y^{-1}. Ethanol quantities are based on a conversion rate of 0.292 m^{3} Mg^{-1} of stover. Marginal transportation distance is 53 km for the smallest plant output level under both bale regimes, except for densified stover harvested as round bales, with a marginal distance of 56 km. Harvest area is greater under the round-bale regime (6.6 Mm^{2} for undensified and 5.8 Mm^{2} for

Table 3 – Stover demand and marginal costs, counties, and distance for each plant output level and bale type

Ethanol Output ($hm^3 y^{-1}$)	Stover demand (Tg)	Marginal cost ($\$ Mg^{-1}$)	Marginal cost ($\$ m^{-3}$ ethanol)	Marginal transport distance (km)	Total harvest area (Mm^2)
Round bales (figures in parentheses are for densified case)					
0.095	0.325	62 (78)	210 (270)	53 (56)	6.053 (5.763)
0.189	0.649	72 (84)	240 (290)	79	12.598
0.379	1.298	82 (88)	280 (300)	116	25.294
0.568	1.947	86 (90)	300 (310)	163	37.982
0.757	2.597	93 (95)	320 (320)	183	51.365 (51.499)
Rectangular bales (figures in parentheses are for densified case)					
0.095	0.325	55 (79)	190 (270)	53	4.325
0.189	0.649	60 (84)	200 (290)	77	9.189
0.379	1.298	62 (87)	210 (300)	88	18.783
0.568	1.947	66 (90)	230 (310)	124	28.024
0.757	2.597	68 (93)	240 (320)	163	37.982

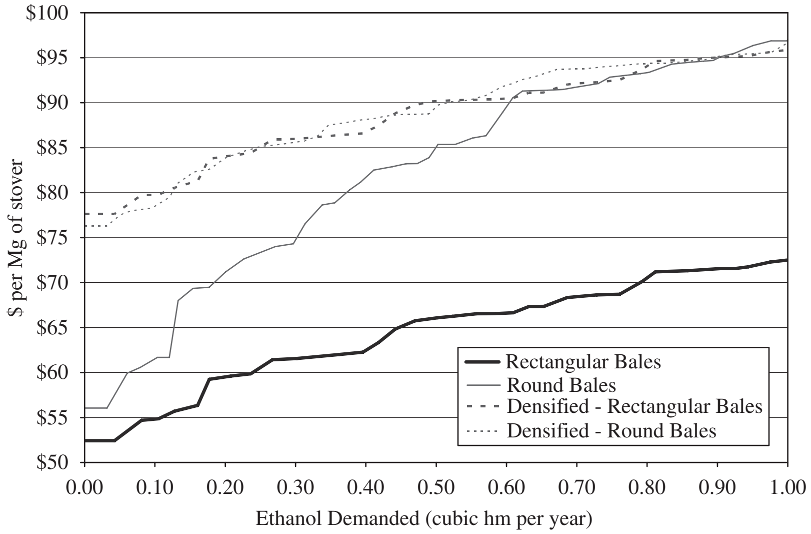

Fig. 2 – Cost per Mg of stover feedstock for given ethanol output levels under each bale and densification regime.

densified) than that of square bales (4.8 Mm^2). Densification did not affect marginal transport distance or harvest area for stover harvested as rectangular bales. As output increases, marginal transport distance and harvest area increase; this occurs at a faster rate under the round-bale system. The greatest difference in marginal transportation distance between the two systems is 39 km, at the 0.568 $hm^3 y^{-1}$ output level, and the greatest difference in harvest area is 14 Mm^2 at the 0.757 hm^3 output level.

Regarding cost, the undensified rectangular-bale method was cheaper for all plant output levels (see Fig. 2). It was hypothesized that the rectangular-bale method, although more expensive on a per-hectare basis, would be cheaper on a per-bale and per-Mg basis due to the higher harvest efficiency per hectare. This was found to be false at the county level, as the round-bale harvest method was found to be cheaper on a per-hectare, per-bale, and per-Mg basis. However, the cost curve for the rectangular-bale method was everywhere below that of the round-bale method because although the round-bale method was cheaper per Mg, the rectangular-bale method allowed for more stover to be harvested in each county, and hence the lowest-cost counties were able to contribute more to supply at lower cost. Furthermore, the rectangular-bale method allowed for more mass to be transported per semi, and thus transportation costs were lower for this method. Thus, although the round-bale method was cheaper *within* a given county, the rectangular-bale method was cheaper on the whole. This relationship did not hold for densified stover, however, because the dominant cost difference is transportation cost to the conversion facility, which, under densification, is identical for the two baling systems. The remaining two cost differences, transportation cost to storage (which varies from county to county but is always advantage rectangular bales) and bale storage cost (advantage round bales by about \$7) determine the advantage. If, for a given production level, the difference in transportation cost of the marginal county exceeds \$7, then the rectangular-bale method has the lower cost; otherwise, the round-bale method is lower cost. The result is the crossing pattern exhibited by the two densified-stover curves in Fig. 2.

For a facility producing 0.095 $hm^3 y^{-1}$ ethanol, for example, marginal feedstock cost was estimated at \$62 Mg^{-1} (\$210 m^{-3} of ethanol) using undensified round bales and \$55 Mg^{-1} (\$190 m^{-3} of ethanol) using rectangular bales. As the quantity of stover required increased with plant output, the cost difference between the two bale methods widens, as shown by Fig. 2. As Table 3 shows, marginal feedstock cost increased by \$13 from the smallest to the largest plant size under the rectangular-bale harvest method, but by \$31 under the round-bale method. In terms of ethanol, these differences represent an increase of \$50 m^{-3} versus \$110 m^{-3}.

Furthermore, the results indicate that even at output levels, undensified rectangular bales is the cheapest method. Densification becomes cost competitive with round bales around the 0.600 $hm^3 y^{-1}$ output level, but is still more than \$22 Mg^{-1} more expensive than undensified rectangular bales.

3.1. *Sensitivity analysis*

Monte Carlo simulation was used to conduct sensitivity analysis of key parameters on delivered bale costs. The parameters tested were crop yields, farmer participation rate, bale moisture content, and stover collection efficiency. In order to conduct this analysis, it was necessary to specify probability distributions for each of the parameters. Very little is known of these distributions, but reasonable assumptions could be made in order to conduct the analysis. For crop yields, a discrete uniform distribution was assumed such that yields from any of the 5 years during 2000–2004 were equally likely to occur. Note that all of the counties experienced a given year's yields together; i.e., one county's 2000 yield could not be assumed while another county experienced yields from 2003. For farmer participation rate, nothing is known that would indicate what sort of probability distribution would exist; therefore, a uniform distribution with a minimum of 25 percent and a maximum of 75 percent was used.

For bale moisture content, a variety of data exist. In an experimental setting, Womac et al. [30] estimated a mean moisture content and standard deviation of combine-harvested corn stover of 16 and 11 percent, respectively. The experiments of [9] resulted in moisture content levels of 13.9, 14.3, and 33 percent for round bales, and 30 percent for stacks. Schechinger and Hettenhaus [8] reported that during the 1997–98 harvest, moisture ranged between 11 and 35 percent, averaging just under 27 percent. A 1966 study referenced by [29] reports moisture levels of cobs, husks, and stalks and leaves at 19, 24, and 33 percent, respectively, when grain is at 15 percent moisture. Other studies have assumed moisture levels of 25 percent [3] and 20 percent [4]. Given that this range of estimates is centered around 15–20 percent and appears to be positively skewed (values tend toward the lower end of the scale), it was decided to assume a log-normal distribution with the mean and standard deviation reported in [30], truncated at 80 percent moisture content.

Finally, there is very little certainty concerning stover collection efficiency. Estimates range from around 25 percent (round bales and stacks in [9,29]), to 40 percent (round and rectangular bales [4]; round bales in [8]), to 70 percent (rectangular bales [8]). With this meager amount of information, a triangular distribution was chosen, with a minimum, mode, and maximum of 25, 30, and 50 percent for the round-bale method, and 30, 40, and 70 percent for the rectangular-bale method. Crystal Ball simulation software [31] was used in conjunction with Microsoft Excel to randomly draw values for each variable from each distribution and calculate the resulting delivered stover cost 10,000 times. It was hypothesized that tillage practice would impact results during sensitivity analysis because collection efficiency would be allowed to vary simultaneously. For this reason, four simulations were run separately, assuming round and rectangular bales under both current tillage and no-till practices. Because densification adds a constant per-Mg cost to the total costs and because its impact on transportation cost is small, sensitivity analysis was not conducted on the densified stover scenarios.

3.2. *Sensitivity analysis results*

Note that this analysis was done only for output of 0.189 $hm^3 y^{-1}$, and that reported costs are marginal costs per Mg of stover delivered. The mean marginal cost for the rectangular-bale method under both tillage practices was about \$57 Mg^{-1}, with a standard deviation around \$12. For the round-bale method, mean and standard deviation were about \$69 and \$10, respectively. A statistical test of the means between the two rectangular-bale scenarios and the two round-bale scenarios under alternative tillage practices concluded that they were not significantly different; i.e., the hypothesis that choice of tillage practice does not significantly impact mean stover cost, even when collection efficiency is allowed to vary, could not be rejected. The stover-cost probability distribution functions are truncated at the upper tails for esthetic purposes.

As Figs. 3–6 illustrate, under the given probability distribution assumptions of the independent variables, stover cost exhibits a log-normal probability distribution, with costs most likely to fall in the \$44 to \$66 range for rectangular bales, and in the \$55 to \$77 range for round bales. Although the probability distribution functions for the round-bale scenarios, as illustrated, are bi-modal, this is simply a consequence of lumpy data, and has to do, primarily, with the value taken by the farmer participation rate. *Ceteris paribus,* when farmer participation rate is specified at 65 percent, marginal stover cost for the round-bale method is \$61 Mg^{-1}; when it decreases to 64 percent, it jumps to \$66. Thus, cost only takes on a value between \$62 and \$65 (the range of cost values found in the trough between the two peaks in Figs. 5 and 6) rarely, when the values of the other parameters combine with the farmer participation rate in such a way to bring that about. Although the same phenomenon occurs with the rectangular-bale method, this trough does not appear in Figs. 3 and 4 because the gap between cost values is smaller and imperceptible as illustrated.

In terms of percentiles, 90 percent of simulated costs were below \$68 for rectangular bales, and below \$78 for round bales. Thus, even with the wide swings in assumptions tested

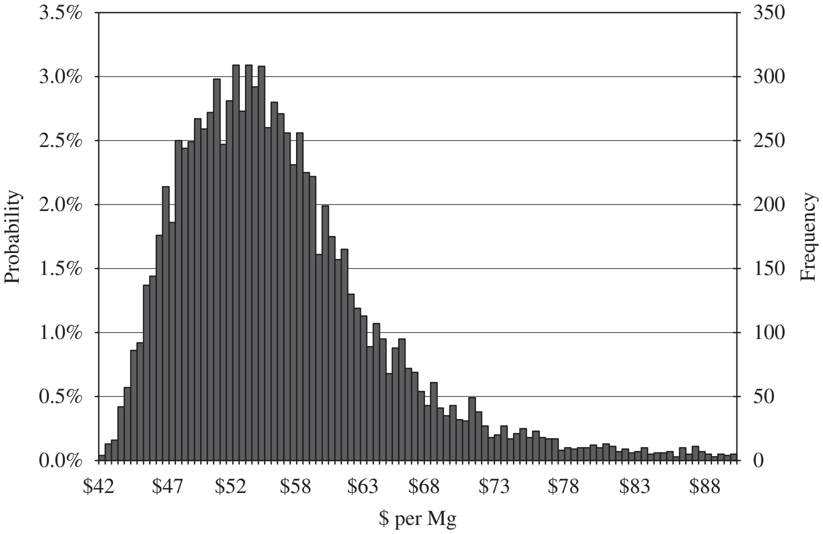

Fig. 3 – Probability distribution of marginal costs: current tillage and rectangular-bale method.

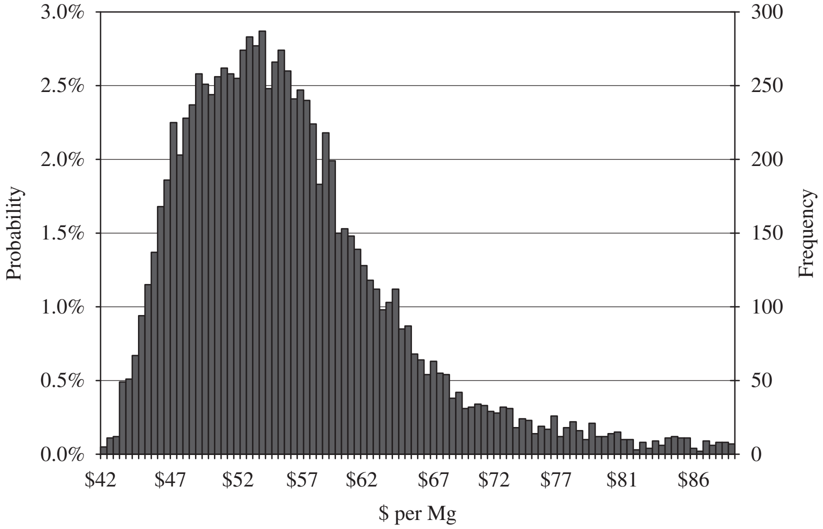

Fig. 4 – Probability distribution of marginal costs: no-till and rectangular-bale method.

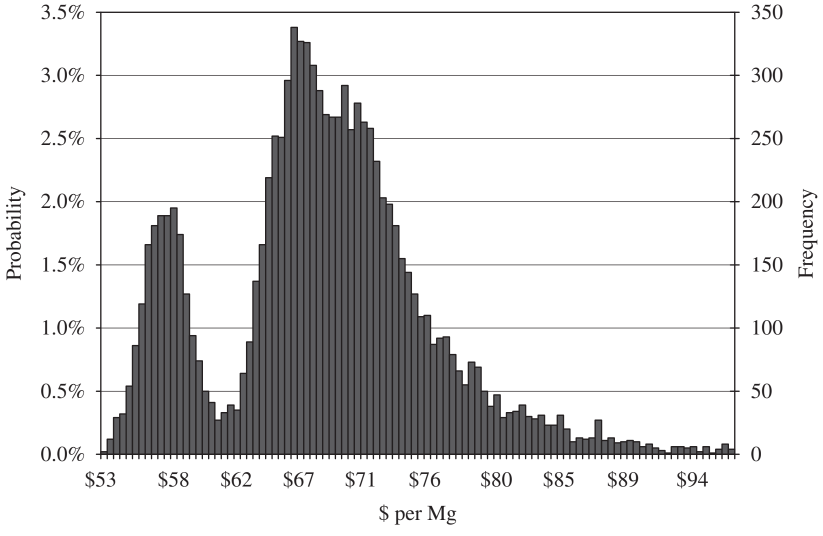

Fig. 5 – Probability distribution of marginal costs: current tillage and round-bale method.

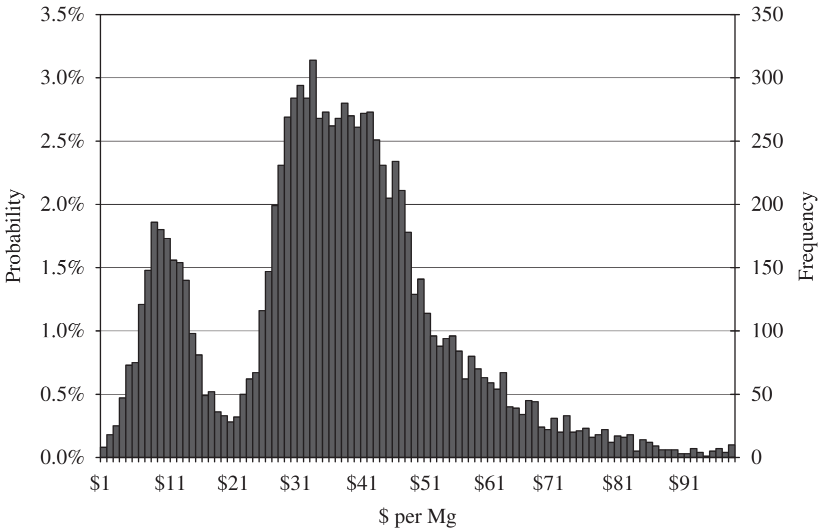

Fig. 6 – Probability distribution of marginal costs: no-till and round-bale method.

here, costs would still most likely fall within the $11 of the mean. However, in terms of $\$\,m^{-3}$ of ethanol, a swing of $\$11\,Mg^{-1}$ of stover represents a swing of $\$40\,m^{-3}$ of ethanol. Thus, while this range may be considered small, it may indeed be significant in terms of predicting expected profits of an ethanol facility.

In addition to the probability distribution, rank correlation coefficients were calculated between the dependent variable (corn-stover cost) and each independent variable. Rank correlation, which is a measure of the strength of association between two variables, is calculated by ranking all observations of each variable, and then computing the correlation between the ranks of each pair of variables. For rectangular bales, rank correlation between stover cost and bale-moisture content was around 0.70, -0.49 for collection efficiency, and -0.27 for farmer participation rate. Thus, for rectangular bales, cost appears to be more heavily influenced by moisture content (positive), then by collection efficiency (negative), and then by farmer participation rate (negative). Influence on cost of round bales, however, was more even, with each parameter rank correlation coefficient around 0.50 (absolute value). These results, as well as the shape of the probability distribution function (log normal) indicate that bale moisture content contributed (positively) significantly to determining cost, and that it played a relatively greater role for rectangular bales than for round. Furthermore, the opposite was true for farmer participation rate, which negatively influenced the marginal cost of round bales more than square. Note that no correlation coefficient is reported for crop yield due to the way in which crop yields were determined during simulation; it was not possible to calculate a coefficient that was meaningful.

4. Conclusions

The results here indicate that, in general, cost per Mg of stover does not increase drastically as increased ethanol output levels are assumed, all else equal. In terms of m^3 of ethanol, the increase is about $\$50\,m^{-3}$. However, sensitivity analysis revealed that costs can fluctuate substantially when different assumptions of key parameters are assumed, although they are most likely to vary by no more than about $\$70\,m^{-3}$ ($\$22\,Mg^{-1}$). Thus, this work offers some idea as to the certainty range of costs of stover collection and transport.

Among other things, this work is limited by its assumptions on collection technology; it is likely that if corn stover catches on as a major fuel feedstock that new, more efficient techniques will be developed that will drive down costs. Additionally, it is expected that research will lead to more efficient cellulase enzymes that will result in more ethanol per ton of stover, hence reducing the quantity of stover necessary for a given quantity of ethanol. This study assumed an ethanol yield that may be considered conservative ($0.292\,m^3\,Mg^{-1}$) relative to that assumed in [32] ($0.374\,m^3\,Mg^{-1}$). Furthermore, if removal of stover from farm fields turns out to have no substantial negative consequences in terms of erosion, soil-carbon levels, and field readiness for the next year's crop, then it is likely that more farmers will be willing to offer stover each year. Finally, it is likely that once such facilities are operational, it would be optimal to identify alternative feedstocks to use throughout the year in order to reduce or eliminate the need for long-term storage of corn stover, which, under the current estimates, adds between $8 and $\$14\,Mg^{-1}$. It is reasonable to envision a facility processing corn stover in the fall, but processing a different feedstock, such as winter wheat straw during the winter and switchgrass during the summer. All of these have the potential for either dramatically increasing the quantity of feedstock available in close proximity to the plant or reducing costs, and hence the potential for substantially lower stover-derived ethanol costs. Note well, however, that these estimates do not include any payment to the farmer, other than for replacement of removed nutrients. It is likely that some additional payment reflecting market conditions will be required to create the necessary incentive for farmers to make their stover available.

Finally, it is of critical importance to determine the impact of corn-stover cost uncertainty on expected conversion-facility profitability. As was noted in the sensitivity analysis, one standard deviation from the mean estimated cost of a Mg of stover translates into a $\$40\,\mathrm{m}^{-3}$ swing in ethanol cost. Research investigating ways in which this uncertainty can be reduced or how the financial risk associated with this uncertainty may be handled is the subject of future research.

Acknowledgements

The author would like to thank Ralph P. Overend, Vernon Eidman, and Doug Tiffany for reviewing this manuscript, and to Bill Lazarus, Jerry Fruin, and Steve Taff for reviewing earlier versions. Funding for this research was from a University of Minnesota Initiative for Renewable Energy and the Environment grant “Liquid Fuels from Biomass: An Integrated Biorefinery Approach”.

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