Staff Paper P06-12 August 2006

Staff Paper Series

The Economics of Harvesting and Transporting Corn Stover for Conversion to Fuel Ethanol: A Case Study for Minnesota

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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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Abstract

Corn stover harvest and transport cost functions were estimated for two harvest operations for a proposed biomass-to-ethanol conversion facility located in southern Minnesota, USA. This work presents an alternative methodology to estimating corn stover quantities and harvest costs at the county level, taking into account county-specific yields, transportation distances, erosion constraints, machinery specifications, and other key variables. Monte Carlo simulation was also used to estimate the probability distribution of costs under alternative assumption on key parameters whose values vary widely in the literature. Marginal stover cost for 50MM gal/year of ethanol output was estimated at $54/dt ($0.77/gal ethanol) for the more intensive harvest method and $65/dt ($0.80/gal) for the less intensive method. Costs were greater than $62/dt ($0.89/gal) for a facility producing > 200MM gal/year under the more intensive harvest method, and greater than $84/dt ($1.21/gal) for the less-intensive harvest method. Monte Carlo simulation estimated a mean marginal cost of $52/dt ($63/dt under the less intensive harvest method) for 50MM gal ethanol output, with an $11 ($9) standard deviation. Costs were found to be at or below $62/dt 90 percent of the time ($71/dt for the less-intensive method). An $11/dt standard deviation in stover cost would result in a $0.16/gal swing in ethanol cost. Overall, costs were found to be consistently higher than those found in the literature, but even under a variety of parameter assumptions, costs tended to stay within a $10/dt range of the mean.

Keywords: biomass, corn stover, economics, ethanol, lignocellulose, Monte Carlo

I. Introduction

Concerns surrounding the dependence on rogue states for oil as well as the recent spike in oil prices have resulted in widespread efforts to secure new domestic sources of energy. 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 75 million dry tons (US) of corn stover annually; by comparison, the next most abundant agricultural source of biomass is manure, at 35 million dry tons annually (Perlack et al., 2005).

The objective of this work is to derive a corn-stover cost function specifically for a proposed biomass-to-ethanol facility located in Fairmont, Minnesota. Its focus is on the methods used to estimate delivered stover costs and their application to the proposed Minnesota site. Previous work has attempted to estimate costs of collection and transportation of corn stover, but the estimates presented are very general, and do not account for variations in yield and transportation distance, two of the key variables in determining the economic feasibility of stover as a fuel feedstock. For example, Gallagher et al. (2003) estimated costs of corn stover collection and transport using the same cost parameters for all counties and crops, although they did allow yields and nutrient-replacement costs to vary across counties. Perlack and Turhollow (2003) present a thorough analysis of machinery costs specific to corn stover, but this study assumed a single value for corn yield, stover yield, and corn acreage density over a 14,000 square-mile collection area. Sokhansanj and Turhollow (2002) assumed a single corn yield, stover yield, and transportation distance for their work. Sayler and Von Bargen (1993) comes to closest to the current study in terms of methodology, focusing on a specific facility location and specific counties in Nebraska, adjusting for erosion constraints using county-level data, and presenting a detailed account of field operations. However, they made simplifying assumptions on stover yields, is focused on southern Nebraska, and the study itself is 13 years old. The possible exception to these studies is a GIS-based cost-estimation model developed by Graham, English, and Noon (2000). Unfortunately, the results presented in there were for switchgrass, not corn stover, and when the model was used for corn stover collection by Sheehan et al. (2004), its focus was on Iowa, and no details were provided as to how the estimates were derived. It should be noted, however, that these studies are an excellent source of technical data such as machine parameters, assumptions on bale size, mass, density, etc.

In contrast to the works cited above, Schechinger and Hettenhaus (2004) detailed an actual stover collection project, recounting the experiences of stover collection in Iowa and Wisconsin. This paper is a non-technical report that gives clear, easy-to-read descriptions of the methods used with good discussions of problems encountered and practical advice. Finally, the work of Richey, Liljedahl, and Lechtenberg (1982) must be mentioned. Theirs was an analysis of a small stover-collection experiment at Purdue University, and may be *the* seminal corn-stover collection study.

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 Walsh (2005), 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. Although the desired results are location specific, this work also offers a conceptual framework for estimating quantities and costs of stover collection, transport, and storage. Additionally, this study can be considered a spreadsheet-based alternative to the GIS-based model presented by Graham, English, and Noon (2000). Also, this study presents the results of sensitivity analysis 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 the present researcher was interested primarily in the potential of corn stover to be converted into fuel ethanol, in addition to results in terms of tons of stover and costs per ton, this work presents results in terms of gallons of ethanol produced and costs in terms of dollars per gallon of ethanol. It should be noted well that the cellulose-to-ethanol technology is still in its preliminary stages, and that no commercial facilities exist, although Iogen Corporation claims that their technology is now ready for commercial use. Issues surrounding the implementation of such facilities, financing, market conditions, etc., are critical to the success of this technology, but are beyond the scope of this work.

II. Conceptual Framework

II.A. Corn Stover Production

Please refer to Table 1 as a guide to notation used throughout this section. The best available data on stover quantities is derived from county-level corn yield estimates from USDA-NASS (2005). Therefore, for each county, a single quantity of stover available will be determined based on county level corn acres harvested, corn yields, and assumed collection efficiency. This single quantity can be conceived of as coming from a stover yield function of the following form. Let Q_i be the quantity of corn stover produced in county i (in bone-dry lbs). Then

$$Q_i = a_i y_i \tag{1}$$

where a_i is the number of acres harvested in county i, and y_i is the average county yield in lbs per acre reported for county i (it is assumed that the dry-weight ratio of stover to corn grain is 1:1). Let q_i be the per-acre quantity of corn stover that could be harvested in county i:

$$q_i = y_i \tag{2}$$

Now, once the total quantity of stover produced is determined, it is necessary to compare that quantity to the quantity of stover that can be technically harvested as well as the quantity that must remain in the field to satisfy erosion, soil-organic carbon, and other environmental constraints for a given tillage practice. Let $0 \leq h^m \leq 1$ represent the harvest efficiency of harvest method m, where $h^m = 1$ indicates that 100 percent of the stover in the field can actually be collected and baled, let e_i^t represent the per-acre quantity that must remain in the field due to erosion constraints for county i under tillage practice t, and let s_i^{tm} represent the per-acre quantity of stover that can actually be removed given erosion and technology constraints. Further, it is assumed that the quantity that can actually be removed is equal to the quantity actually collected. Then,

$$\text{if } q_i - e_i^t \geq q_i h^m \text{, then } s_i^{tm} = q_i h^m \tag{3}$$

and

$$\text{if } q_i - e_i^t < q_i h^m \text{, then } s_i^{tm} = q_i - e_i^t . \tag{4}$$

Equations (3) and (3’) can be condensed into

$$s_i^{tm} = \mathrm{Min}(q_i h^m, q_i - e_i^t) . \tag{5}$$

Furthermore, let S_i^{tm} be the total quantity of stover collected in county i under tillage practice t and collection method m, such that

$$S_i^{tm} = a_i p [\mathrm{Min}(q_i h^m, q_i - e_i^t)] \tag{6}$$

where p is the participation rate of farmers (assumed to be identical for all counties).

II.B. Collection costs

Let c_i^{tm} be the collection cost per acre for collection method m for an acre under tillage practice t in county i. Collection cost per ton will vary across counties and will depend on stover collected per acre (which depends on corn yield). Therefore, per-ton collection cost for collection method m under tillage practice t in county i can be represented as:

$$\tilde{c}_i^{tm} = c_i^{tm} / s_i^{tm} \qquad (7)$$

for $s_i^{tm} > 0$, and undefined otherwise.

II.C. Nutrient replacement cost

Let n_i^{tm} be the nutrient (fertilizer) replacement cost per acre under tillage method t for collection method m in county i. Nutrient replacement cost per ton will vary across counties and will depend on quantitiy of stover collected per acre. Therefore, nutrient replacement cost per ton in county i can be represented as:

$$\tilde{n}_i^{tm} = n_i^{tm} / s_i^{tm} \qquad (8)$$

for $s_i^{tm} > 0$, and undefined otherwise.

II.D. Transportation Costs

Let $\tilde{x}^z$ be the 1-ton-per-mile cost of transporting stover using method z, and let d_{ij} be the travel distance from each county node i to each potential plant node j. Each truck is assumed to return to its origin after delivery, and thus cost is a roundtrip estimate. Thus, the total roundtrip transportation cost for a ton of stover from county i to plant j will be:

$$\tilde{x}_{ij}^z = 2\,\tilde{x}^z d_{ij}. \qquad (9)$$

II.E. Total Delivered Cost

Therefore, the total delivered cost $\tilde{C}_{ij}^{tmz}$ of collecting, transporting, and storing 1 ton of stover from county i under tillage practice t to plant j, using collection method m and transportation method z can be represented by the function:

$$\tilde{C}_{ij}^{tmz} = \tilde{c}_i^{tm} + \tilde{x}_{ij}^{z} + \tilde{n}_i^{tm} + \tilde{u} + b^m \tag{10}$$

where $\tilde{u}$ is the per-ton cost of unloading and stacking the stover at the plant and b^m is the per-ton cost of storage for bales collected using collection method m.

Substituting equations (2), (5), (7), (8), and (9) into (10) yields:

$$\tilde{C}_{ij}^{tmz} = (c_i^{tm} + n_i^{m}) / \mathrm{Min}(y_i h^m, y_i - e_i^t) + \tilde{x}^z d_{ij} + \tilde{u} + b^m . \tag{11}$$

for $\mathrm{Min}(y_i h^m, y_i - e_i^t) > 0$, and undefined otherwise.

III. Applied Analysis

The above framework was applied to a case study of a proposed corn-stover-to-ethanol facility located in Fairmont, Minnesota.[1] It was assumed that this facility would be able to draw stover supplies from all of Minnesota and border counties in Iowa, South Dakota, and Wisconsin. However, harvest was restricted to those counties with average annual corn production of at least 10 million bushels (see Figure 1).[2] It was first necessary to estimate the total quantity of stover produced and available for harvest, which was accomplished by obtaining annual county-level corn production data as well as quantities of stover that can be removed such that erosion constraints were satisfied. It was then necessary to estimate the feasible quantity of

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[1] The location of the plant is somewhat arbitrary. Martin County, where Fairmont is located, is 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 is likely, however, that many of the surrounding counties would have equal potential.

[2] The resulting study area covers a total of 54,252 square miles. None of the Wisconsin border counties met the production threshold.

stover that could be removed with the existing technology; this required the construction of machinery sets and estimates of per-hour, per-acre, per-bale, and per-ton costs for each machine operation. These results were then combined with transportation cost estimates and other direct costs to arrive at county-specific delivered costs, which, when combined, produced a corn-stover cost function for the Minnesota conversion facility. Table 2 contains the values for parameters assumed throughout the analysis.

III.A. Estimate of Stover Quantities

Acres harvested and corn yields were obtained from USDA-NASS (2005) for the years 2000-2004. Bone-dry weight of a bushel of corn grain was assumed to be 47 lbs (Larson, Holt, and Carlson, 1978).[3] Walsh (2005) reported quantities of stover necessary to remain in the field for two tillage regimes: current mix of tillage practices and all no-till. Walsh's estimates account for wind and water erosion only, and were estimated such that erosion is kept at or below tolerable soil-loss levels. A 50-percent farmer participation rate was assumed and tested for sensitivity later in the analysis.

III.B. 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

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[3] There is, apparently, some controversy surrounding this ratio. Larson, Holt, and Carlson (1978) based their "dry weight" ratio on a bushel weight of 56 lbs. This weight is generally associated with a grain moisture content of 15.5 percent, thus their ratio implicitly assumes that the stover will have an equal moisture content. This implicit assumption is confirmed somewhat by the results of Womac, Igathinathane, Sokhansanj, and Pordesimo (2005), who report a stover moisture content of 16 percent when grain is combine-harvested at 15 percent moisture. Thus, for bone-dry weight, one should multiply the quantities of stover calculated using the 56 lbs/bu standard by approximately 0.84. Other studies, however, have based their bone-dry estimates on the 56 lb/bu figure, thus over-estimating the amount of dry stover actually available.

was assumed that this method collects 30 percent of total stover produced.[4] 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 (square) baler. It was assumed that this method collects 40 percent of total stover.[5] The assumptions on collection efficiency were tested for sensitivity later in the analysis.

Table 3 contains the set of operations, machinery, and cost information for the two collection operations. A John Deere 557 round baler pulled by a 60 HP tractor was assumed to be used that would produce 62" wide x 54" diameter bales weighing 739 lbs (dry) (assuming 8.99 lbs/ft^3 density). A larger baler was initially used based on a bale size of 62" x 72", as used in Sokhansanj and Turhollow (2002), Schechinger and Hettenhaus (2004), and Perlack and Turhollow (2002). However, these bales were too wide to load two across on a standard semi-trailer without exceeding Minnesota highway trailer restrictions. Thus, the smaller baler producing smaller bales was used. Based on the recommendations of Schechinger and Hettenhaus (2004), the optional mega-tooth pickup and high-moisture kit were added to the baler cost. 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. Further, round bales in Schechinger and Hettenhaus (2004) were wrapped in plastic three times around,

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[4] This may be a conservative estimate. Schechinger and Hettenhaus (2004) reported that this collection method collected 40-50 percent of total stover; however, they also report that the average amount collected in the part of the project that relied more heavily on this method averaged 1.25 dry tons per acre, which is not necessarily consistent with a 45-percent estimate. Forty-five percent implies a total stover quantity of 2.78 tons, which is a little more than half of the total estimated for counties in this study. Using their 1.25-ton figure and the average quantity of stover production estimated here (3.85 tons/acre), we get a figure of 32 percent.

[5] This may be a conservative estimate. Schechinger and Hettenhaus (2004) reported that this collection method collected up to 70 percent of total stover; however, they also report that the average amount collected in the part of the project that relied more heavily on this method averaged 1.55 dry tons, which is not necessarily consistent with a 70-percent estimate. Seventy percent implies a total stover quantity of 2.21 tons, which is about half of the total estimated for counties in this study. Using their 1.55-ton figure and the average quantity of stover produced estimated here (3.85 tons/acre), we get a figure of 40 percent.

so this assumption was also used here. Once the stover was baled, it was assumed that an Inland 2500 automated bale picker pulled by a 130 HP tractor would collect the bales from the field and transport them to the field edge to be loaded on semi trailers. The Inland 2500 has a capacity of 14 round bales. A John Deere 3220 Telehandler with a Frontier Bale Hugger attachment was assumed to be used to transfer bales from the Inland to the semi trailer.

For the square-bale method, it was assumed that a 20-ft stalk shredder pulled by a 130 HP tractor would make the first pass over the spread stover, followed by a John Deere 705 Twin Rake pulled by a 60 HP tractor to form the windrows. A Hesston 4790 large square baler pulled by a 130 HP tractor would then be used to bale the windrows, producing bales 36” high x 48” wide x 96” long, weighing 1,342 lbs (dry) (assuming a density of 13.98 lbs/ft^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. Square bales were assumed to be held together with twine, and a knotter cleaner attachment was added to the baler to reduce knotter problems. Bales were then assumed to be collected and moved to the field edge using an Inland 4000 bale picker, with a capacity of 8 square bales. A John Deere 3220 Telehandler fitted with a Frontier Bale Squeezer would then be used to transfer the bales to a semi trailer.

Tractor and stalk shredder purchase prices were taken from Lazarus and Selley (2005), whereas baler and baler-attachment price data were taken from Iron Solutions (2005). Bale-wrap and twine costs were taken from Schechinger and Hettenhaus (2004), and bale-picker prices were obtained from Yeo (2005). Rake and telehandler prices were taken from John Deere (2005). All per-hour machinery costs were estimated using Lazarus and Selley’s machinery cost spreadsheet (2005), as were the per-acre 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 hours annually and all other machinery was used 250 hours annually.

Per-bale costs of bale wrap and twine were taken directly from Schechinger and Hettenhaus (2004). 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 x 14 round bales per hour and 3 x 8 square bales per hour).[6] Per-bale cost for the telehandler was calculated from the per-hour cost using Sokhansanj and Turhollow's (2002) assumption that 48 bales could be transferred per hour.[7] The remaining per-bale costs and per-acre costs were specific to each county because they depended on the quantity of stover available per acre. Per-ton costs were a direct conversion from per-bale costs.

III.C. 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. Larson, Holt, and Carlson (1978) report that corn residue consists of 0.18% P and 1.33% K. In terms of quantity of fertilizer, these percentages translate into 8.0

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[6] Yeo (2005) mentioned that some farmers were able to collect up to 80 round bales per hour. I assumed a rate of half that, rounded up to the next full load. Sokhansanj and Turhollow (2002) reported conflicting collection rates for their bale mover: They reported a machine capacity of 1 ha/hr for the bale mover and an assumption of 3.72 Mg/ha (dry) of stover baled; thus, they implicitly report a collection rate of 3.72Mg/hr (dry). However, in the very next column they reported a rate of work of 6.23 Mg/hr, which would be 1.67 ha/hr, not one. Furthermore, in terms of 577 kg round bales, these two rates translate into 6.5 bales (3.72 Mg) and 10.8 bales (6.23 Mg) per hour. However, in the *next* column, they reported a rate of work of 14 bales/hr.

[7] Sokhansanj and Turhollow (2002) report a rate of work for their telescopic handler of 37.09 Mg/hour, which, assuming a bale size of 577 kg, is 64 bales per hour. However, in the next column, they reported a rate of work of 48 bales/hr.

lbs of phosphate and 44.3 lbs of potash per ton of stover removed.[8] Schechinger and Hettenhaus (2004) report replacement quantities of 7.0 lbs of phosphate and 35 lbs of potash, and Nielsen (1995) reports 3.6 lbs of phosphate and 19.7 lbs of potash per ton of stover removed. Taking the average of the three, it is necessary to replace 6.2 lbs of phosphate and 33.0 lbs of potash per ton of stover removed. USDA (2006) reports 2000-2004 average phosphate ("superphosphate") and potash (potassium chloride) fertilizer prices of $0.12 and $0.08/lb, respectively, resulting in an average nutrient replacement cost of $4.21/dry ton of stover removed.

III.D. Transportation

Distance from each Minnesota county was based on distance from the county seat to Fairmont, and was taken from the Official Minnesota Highway Mileage Tables (State of Minnesota, 1976). Distance from each county seat for border states was calculated using the Rand-McNally online distance calculator (2005). There are several issues to consider for transportation and storage, and Perlack and Turhollow (2002) present a good discussion of them. The first issue is whether the bales will be hauled directly to storage in a bale mover pulled by a farm tractor or staged at the field edge then loaded onto flatbeds pulled by semis. The second issue is the number and location of the storage sites themselves. One could assume many small storage sites located close to the fields or one (or a few) storage site(s) located close to the plant. The third issue is the method of transportation from storage to plant. In the project reported in Schechinger and Hettenhaus (2004), semi trucks were used for the portion of the project dealing mostly with square bales, but for round bales, self-contained bale movers pulled by tractors (some high-speed tractors) were used. They reported that given identical loads, a high-speed

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[8] This calculation assumes the use of phosphate fertilizer that is 45% P, and potash that is 60% K.

farm tractor had a cost advantage over a semi-truck for a 70-mile round trip.[9] Sokhansanj and Turhollow (2002) assumed that round bales were transported directly from the field to storage (5 miles away) with a bale mover pulled by a tractor, whereas square bales were transported in a self-propelled bale stacker-mover. They gave no discussion of transportation from storage to the plant. Perlack and Turhollow (2002) noted that the key differences are bale-carrying capacity and loading/unloading operations. Trucks with flatbed trailers carry a larger load but need to be loaded and unloaded with telescopic handlers; self-loading bale movers pulled by a tractor carry smaller loads and are more expensive to operate, but do not require separate loading and unloading equipment. They concluded that for round bales, direct hauling with bale movers was cheaper than staging and hauling with semis (up to a facility size of 3,000 dry tons/day). For square bales, however, they found that staging and hauling with semis was cheaper for all but the smallest facility size. Their distance from field to storage was between 3.1 and 8.7 miles (one way). They concluded in their discussion on transport from storage to plant, however, that high-speed tractors pulling bale wagons were not cost competitive with trucks beyond a haul distance of a "few miles".

It was assumed in this report that all baled stover would be staged at the field edge then transported to storage by semi trucks to regional storage sites. Distance from field to storage was assumed to be 5/12 of the square-root of each county's total land area, and costs were based on a round trip.[10] Distance from storage to conversion facility was assumed to be equal to the

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[9] The comparison using identical loads seems irrelevant. Semis can haul larger loads, which along with the speed advantage, are the main reasons for preferring them over farm tractors.

[10] It was assumed that storage sites would be 10 acres in size, which results in an average of 1.5 sites per county. Assuming a square county, the square root of the area yields the length of one side, and half that is the radius. The furthest distance traveled in a county to a storage site is from a corner; assuming that the travel path forms an "L" shape, this distance from the field to the storage site is 5/12 of the square-root of the area.

distance from county seat to Fairmont, MN. For delivery of stover to a plant located in the same county, the distance was calculated by taking ½ of the square root of the county total area.[11]

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 23 tons (Fruin, 2005). However, this maximum may not necessarily be achieved. It was assumed that the semi trailer has 9' x 9' x 48' of cargo space, bales have a 16-percent moisture content, and that the dry density of round and square bales is 8.99 and 13.98 lbs/ft^3, respectively. The trailer dimensions would thus allow for 3 high x 2 wide x 6 long = 36 square bales; however, such a load would exceed the weight limit of 46,000 lbs. Thus, 27 square bales could be loaded for a total weight of 44,736 lbs. For round bales, the trailer dimensions would allow for 2 bottom rows and one top row of 9 bales each, for a total of 27 bales. This load would weigh only 23,760 lbs.[12] The cost per loaded mile was assumed to be $3.60 for loads within 25 miles of the plant, $2.35 for loads between 26 and 100 miles, and $1.90 for loads traveling greater than 100 miles (USDA-AMS, 2006). 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: $3.10 and $1.71 per ton for round bales and square bales, respectively.

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[11] The square root of the area gives the average of the height and width of the county; for simplicity of this calculation, it is assumed that the plant is located in the center of the county; the greatest travel distance is from a corner of the county; it is assumed that travel would be a right-angle path to the plant; therefore, that distance would be 2 times half the square root of the radius, and that figure is halved to derive the average distance traveled from any point in the county to the plant.

[12] This result calls into question the assumption of Perlack and Turhollow (2003), who assume that 29 1.8 m x 1.5 m round bales weighing 768 kg each could be transported on a 16.2 m semi trailer, and hence, nearly max out the assumed legal 22,680 kg (46,000 lbs) load limit. The problem is that two of these bales placed side by side would exceed the standard 2.6 m width maximum set by the State of Minnesota. Thus, unless they are assuming over-sized loads, their load efficiency is overestimated, and their resulting transport costs are likely underestimated.

III.E. Storage

The window for harvesting corn stover is about 21 days, running from about the middle of October to the beginning of November (Mohr, 2006). 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 (Schechinger and Hettenhaus, 2004). To accommodate equipment and vehicle traffic (driveways, etc.), as well as necessary spacing between bale stacks, it was assumed that the total square footage necessary for the storage site would be twice the square footage of the space required for the bales themselves. Round bales are assumed to be wrapped in plastic, and therefore, can be stored outdoors. Square bales, however, are not wrapped, and would require indoor storage. Square 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 $100 per acre, and land preparation cost, $30,000 per acre. Building cost which was needed for square bales only, was found to range between $1.50 and $6.00 per square foot (Huhnke, 2004; Fruin, Wilcke, and Schmidt, 1995); an average building cost of $3.75 per square foot 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 (Fruin, Wilcke, and Schmidt, 1995). Equipment cost (telescopic handler) was estimated to be $1.15 per bale. Storage costs are independent of the number or location of storage sites; i.e., no economies of scale are assumed for larger storage sites, which may be a simplification. Accounting for all of this information, it was estimated that total storage costs are $12.94 per dry ton for square bales and $7.31 per dry ton for round bales. Although costs are higher for square bales, the total land area needed for storage is about half that of round bales. Furthermore, building costs are critical. If building costs are actually closer to \$1.50 per square foot, then storage cost for square bales is \$6.59 per dry ton; if closer to \$6.00 per square foot, then storage cost is \$18.32 per dry ton. Table 4 contains estimated storage costs, as well as land requirements and other key estimates for each plant output level, assuming 10-acre storage sites.

III.F. Bale Densification

An important issue that is not discussed much in the literature is bale densification into briquettes, pellets, wafers, etc. This process 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. (2006) and Sokhansanj and Turhollow (2004) to establish estimates for densification processes. Their results were incorporated here to estimate costs of including a densification step in the present system.

Mani et al. (2006) reported significant reductions in per-ton cost for larger densification plant sizes relative to smaller ones. Consequently, this report adopted their cost estimates for a 75,000 annual ton facility, which was the second largest facility size reported, with a densification cost of \$23.33 per dry ton.[13] Densification increases stover density from 9 (round bales) and 14 (square bales) to 39 lbs/ft^3 (bulk density). It was assumed that a densification facility would be located at each regional storage site, so that no additional hauling cost 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

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[13] This figure was arrived at by subtracting their estimated raw material cost from the total cost and converting to dry weight assuming 10-percent moisture for densified stover.

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 on-site densified-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-ton transportation cost by half. For square bales, however, the cost reduction is small, as a load of square 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.

IV. 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 five 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 5 contains the estimated marginal cost and transport distance of delivered stover as well as the total square miles of harvest area necessary to supply corn stover for ethanol plant output of 25, 50, 100, 150, and 200 millions gallons annually, respectively. Ethanol quantities are based on a conversion rate of 69.9 gallons per dry ton of stover, which is more conservative than that of Aden et al. (2002), who report a conversion rate of 89.7 gallons per dry ton.

Marginal transportation distance is 33 miles for the smallest plant output level under both bale regimes, except for densified stover harvested as round bales, with a marginal distance of 35 miles. Harvest area is greater under the round-bale regime (2,559 square miles for undensified and 2,225 for densified) than that of square bales (1,857). Densification did not affect marginal transport distance or harvest area for stover harvested as square 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 24 miles, at the 150MM gallon output level, and the greatest difference in harvest area is 5,270 square miles at the 200MM gallon output level. These differences in transport distance and harvest area are more clearly understood by examining Figures 2, 3, and 4 which contain maps of the counties that would supply stover for each increase in plant output (because densification did not affect square bales, Figure 3 represents both the undensified and densified cases).

Regarding cost, the undensified square-bale method was cheaper for all plant output levels (see Figure 4). It was hypothesized that the square-bale method, although more expensive on a per-acre basis, would be cheaper on a per-bale and per-ton basis due to the higher harvest efficiency per acre. This was found to be false at the county level, as the round-bale harvest method was found to be cheaper on a per-acre, per-bale, and per-ton basis. Furthermore, storage costs were found to be more expensive on a per-ton basis for square bales. However, the cost curve for the square-bale method was everywhere below that of the round-bale method because although the round-bale method was cheaper per ton, the square-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 square-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 square-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 square bales) and bale storage cost (advantage round bales by about $6) determine the advantage. If, for a given production level, the difference in transportation cost of the marginal county exceeds $6, then the square-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 Figure 4.

The marginal cost of a 25MM gallon plant, for example, was estimated at $56/dry ton ($0.80/gal of ethanol) using undensified round bales and $50/dry ton ($0.71/gal of ethanol) using square bales. As the quantity of stover required increased with plant output, the cost difference between the two bale methods widens, as shown by Figure 4. As Table 5 shows, marginal cost increased by $12 from the smallest to largest plant size under the square-bale harvest method, but by $28 under the round-bale method. In terms of ethanol, these differences represent an increase of $0.18 versus $0.41 per gallon.

Furthermore, the results indicate that even at output levels, undensified square bales are the cheapest method. Densification becomes cost competitive with round bales around the 150MM gallon output level, but is still more than $20 per ton more expensive than undensified square bales.

V.A. 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 five 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, Igathinathane, Sokhansanj, and Pordesimo (2005) estimated a mean moisture content and standard deviation of combine-harvested corn stover of 16 and 11 percent, respectively. The experiments of Richey, Liljedahl, and Lechtenberg (1982) resulted in moisture content levels of 13.9, 14.3, and 33 percent for round bales, and 30 percent for stacks. Schechinger and Hettenhaus (2004) reported that during the 1997-98 harvest, moisture ranged between 11 and 35 percent, averaging just under 27 percent. Sokhansanj et al. (2002) reference a 1966 study that 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 Perlack and Turhollow (2003) and 20 percent Sokhansanj and Turhollow (2002). 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 Womac et al. (2005), 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 Richey, Likledahl, and Lechtenberg, 1982 and Sokhansanj et al., 2002), to forty percent (round and square bales in Sokhansanj and Turhollow, 2002; round bales in Schechinger and Hettenhaus, 2004), to 70 percent (square bales in Schechinger and Hettenhaus, 2004). 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 square-bale method. Crystal Ball (2006) simulation software 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 square bales under both current tillage and no-till practices. Because densification adds a constant per-ton cost to the total costs and because its impact on transportation costs is small, sensitivity analysis was not conducted on the densified stover scenarios.

V.B. Sensitivity Analysis Results

Table 7 contains the summary statistics for each of the four simulations: square-baling method under current tillage practice and under no-till, and round-baling method under current tillage practice and no-till. Note that this analysis was done only for output of 50MM gallons per-year, and that reported costs are marginal costs per dry ton of stover delivered. The mean marginal cost for the square-bale method under both tillage practices was about $52 per dry ton, with a standard deviation around $11. For the round-bale method, mean and standard deviation were about $63 and $9 respectively. A statistical test of the means between the two square-bale scenarios and the two round-bale scenarios under alternative tillage practices concluded that they were not significantly different, respectively.[14] 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 for the four scenarios are plotted in Figures 3 through 6, respectively.[15]

As Figures 6 through 9 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 $40 to $60 range for square bales, and in the $50 to $70 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 $55 per dry ton; when it decreases to 64 percent, it jumps to $60. Thus, cost only takes on a value between $56 and $59--the range of cost values found in the trough between the two peaks in Figures 8 and 9--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 square-bale

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[14] A visual inspection of the probability distributions of costs revealed log-normal distributions (see Figures 6-9). The data were then transformed into natural logarithms and replotted, which revealed normal distributions. Consequently, a two-sample t-test could be performed on the natural logarithms of the means and variances. With 9,998 degrees freedom and alpha equal to 0.05, t-critical was 1.96; the t-statistic for comparing the square-bale method under different tillage regimes was -0.07; for the round-bale method, it was 0.002.

[15] The probability distribution functions are truncated at the upper tails for aesthetic purposes.

method, this trough does not appear in Figures 6 and 7 because the gap between cost values is smaller and imperceptible as illustrated.

In terms of percentiles, 90 percent of simulated costs were below $62 for square bales, and below $71 for round bales. Thus, even with the wide swings in assumptions tested here, costs would still most likely fall within the $10 of the mean. However, in terms of cost per gallon of ethanol, a swing of $10 per dry ton of stover represents a swing of $0.14 per gallon 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.[16]

In addition to the probability distribution, Crystal Ball also reports rank correlation coefficients 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 then computing the correlation between the ranks of each pair of variables. Reported rank correlations are found in Table 8. For square 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 square bales, cost appear to be more heavily influenced by moisture content (positive), then by collection efficiency (negative), then 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 square 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

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[16] Recall that these estimates do not include any payment to the farmer.

in which crop yields were determined during simulation; it was not possible to calculate a coefficient that was meaningful.

VI. Conclusions

This work synthesized and improved upon past work to derive estimates of what it would cost to harvest and transport stover for the purpose of converting it to fuel ethanol. In addition to offering a general framework, this work presented a case study for a proposed location under a variety of ethanol output levels. Additionally, this work explicitly accounted for differences in costs due to variations in county yields, harvest rates, stover availability, transportation distances, and storage and densification costs. Finally, this work presented the first sensitivity analysis conducted of key cost parameters, using Monte Carlo simulation to estimate probability distribution functions for stover costs over a variety of parameter specifications. The results here indicate that, in general, cost per ton of stover does not increase drastically as increased ethanol output levels are assumed, all else equal. In terms of gallons of ethanol, the increase is about 20 cents per gallon. 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 $0.28 per gallon ($20 per ton stover). 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 (69.9 gallons per dry ton) in comparison to Aden et al. (2002) (89.7 gallons per dry ton) and Iogen Corporation--one of the most well-known cellulose-to-ethanol success stories—who is claiming yields of 81 gallons per dry ton. 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 \$7 and \$13 to the total cost per dry ton. 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 ton of stover translates into a \$0.16 per gallon) 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 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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Table 1. Index and variable reference guide for conceptual framework.

Symbol	**Explanation**
i	index of counties $i = 1, \ldots, I$
m	index of harvest methods, $m = 1, \ldots, M$
t	index of tillage methods, $t = 1, \ldots, T$
j	index of plant locations, $j = 1, \ldots, J$
z	index of transportation methods, $z = 1, \ldots, Z$
Q_i	total stover produced in county i (lbs)
q_i	per-acre stover produced in county i (lbs)
a_i	corn acre in county i
y_i	per-acre corn yield (lbs/ac) in county i
h^m	stover harvest efficiency of harvest method m, $0 \leq h^m \leq 1$
e_i^t	per-acre quantity of stover (lbs) that must remain in the field due to erosion constraints for county i under tillage practice t
S_i^{tm}	total quantity (lbs) of stover collected in county i under tillage practice t and collection method m
s_i^{tm}	per-acre quantity (lbs) of stover harvested given erosion and technology constraints
p	farmer participation rate, $0 \leq p \leq 1$
c_i^{tm}	per-acre harvest cost for harvest method m in county i
$\tilde{c}_i^{tm}$	per-ton collection cost for collection method m under tillage practice t in county i
n_i^{tm}	per-acre nutrient (fertilizer) replacement cost for harvest method m under tillage method t in county i
$\tilde{n}_i^{tm}$	per-ton nutrient (fertilizer) replacement cost for harvest method m under tillage method t in county i
$\tilde{x}^z$	1-ton/mile cost of transporting stover using transport method z
$\tilde{x}_{ij}^z$	total per-ton cost of transporting 1 ton stover from county i to plant j
d_{ij}	travel distance (miles) from each county node i to each potential plant node j
$\tilde{u}$	per-ton cost of unloading and stacking stover at plant storage
$\tilde{C}_{ij}^{tmz}$	total delivered cost of harvesting and transporting 1 ton of stover using harvest method m under tillage practice t from county i to plant j, using transportation method z

Table 2. 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, lbs	47	
Farmer Participation Rate	50%	
Stover to Ethanol Conversion Rate, undenatured gal/dry ton	69.9	
Plant online time, hrs	8406	
Collection	**Round**	**Square**
Stover Collection Efficiency	30%	40%
Bale Size (dia x w / l x w x h), ft	4.5' x 5.17'	8' x 4' x 3'
Dry Bale Density (dry), lbs/ft3	8.99	13.98
Dry Bale Weight, lbs	739	1,342
Bale Moisture Content	16%	
Actual Bale Weight, lbs	880	1,598
Bales picked by bale picker per hour	42	24
Bales moved by telehandler per hour	48	
Transport		
Maximum semi cargo load, lbs	46,000	
Semi trailer usable cargo space, ft	9' x 9' x 48'	
Bales per semi load	27	28
Cargo weight per semi load, lbs	23,760	44,736
Cost per loaded mile (semi-hauled) (0-25 miles)	$3.60	
Cost per loaded mile (semi-hauled) (26-100 miles)	$2.35	
Cost per loaded mile (semi-hauled) (>100 miles)	$1.90	
Unloading/Stacking cost at plant per bale	$1.15	
Storage		
Number of days direct hauled	21	
Storage losses	2%	
Number of square bales stacked high	6	
Number of round bales stacked high	5	
Storage site size, acres	10	
Land costs, $/acre/year	$100	
Land prep, $/acre	$30,000	
Equipment cost (telescopic handler), $/bale	$1.15	
Building Cost, $/sq ft	$3.75	
Building/Land-prep Life, years	20	
Densification		
Densified Stover Bulk Density, lbs/ft3	39.01	
Densified Stover Moisture Content	10%	
Densification Cost, per ton (dry)	$23.33	
Cargo weight per semi load, lbs	46,000	

Table 3. Estimated machine operating costs for collecting corn stover.

Round-Bale Method	**HP**	**List 2005$**	**Purchase**	**Hrs/yr**	**Per-Hour**	**Per-Acre**	**Per-Bale**	**Per-UST**	***Source***
130 HP MFWD Tractor	130	$8,000	$79,200	500					*A*
60 HP Tractor	60	$25,200	$22,680	500					*A*
JD 557 Round Baler	60	$21,311	$19,180	250	$54.27	$10.81			*B*
Megatooth Pickup			$900						*B*
High-moisture kit			$300						*B*
Surface Wrap			$2,900						*B*
Bale Wrap (3 times)				250			$1.70	$4.60	*C*
Inland 2500 Bale Mover	130	$20,775	$18,698	250	$70.99		$1.69	$4.57	*D*
Deere 3220 Telehandler	114	$75,432	$67,889	500	$55.00		$1.15	$3.10	*E*
Deere Frontier Bale Hugger			$1,000						*F*

Square-Bale Method	**HP**	**List 2005$**	**Purchase**	**Hrs/yr**	**Per-Hour**	**Per-Acre**	**Per-Bale**	**Per-UST**	***Source***
130 HP MFWD Tractor	130	$88,000	$79,200	500					*A*
60 HP Tractor	60	$25,200	$22,680	500					*A*
Stalk Shredder 20ft	130	$19,222	$17,300	250	$60.65	$7.82			*A*
JD 705 Twin Rake	60	$13,213	$11,892	250	$32.54	$4.20			*E*
Hesston 4790 Rectangular Baler	130	$82,089	$73,880	250	$98.40	$9.66			*B*
Knotter cleaner			$1,600	250					*B*
Bale Twine				250			$0.72	$1.07	*C*
Inland 4000 Bale Mover	130	$31,795	$28,616	250	$65.50		$2.73	$4.07	*D*
Deere 3220 Telehandler	114	$75,432	$67,889	500	$55.00		$1.15	$1.71	*E*
Deere Frontier Bale Squeezer			$1,000						*F*

Sources:
A: Lazarus (2005),
machdata.xls
B: Iron Solutions NW Region Official Guide Spr 2005, Region D Vol.11 Iss. 1
C: Schechinger & Hettenhaus 2004
D: Personal communication with Jack Yeo, Buhler/Inland, 21 OCT 2005
E: Deere.com "build your own"
F: Price assumed

Table 4. Corn stover storage estimates.

Annual ethanol production, MM gal	**25**	**50**	**100**	**150**	**200**
Stover stored (w/losses), dry tons	343,199	686,398	1,372,796	2,059,194	2,745,592
Stover stored (w/losses), tons as is	408,570	817,140	1,634,281	2,451,421	3,268,562
If Round Bales are used:					
Number of Bales	928,563	1,857,125	3,714,250	5,571,376	7,428,501
Bale Storage area, sq ft	10,369,444	20,738,888	41,477,777	62,216,665	82,955,554
Bale Storage area, acres	238	476	952	1,428	1,904
Number of 10-acre Storage sites	24	48	96	143	191
Number of Bales per site	38,690	38,690	38,690	38,961	38,893
Tons stover per site	17,024	17,024	17,024	17,143	17,113
Number of days supply	14.6	7.3	3.6	2.4	1.8
Annual Land/prep cost	$380,879	$761,759	$1,523,518	$2,285,277	$3,047,036
Annual Equipment cost	$2,127,956	$4,255,912	$8,511,824	$12,767,736	$17,023,648
Total Storage Cost/actual ton	$6.14	$6.14	$6.14	$6.14	$6.14
Total Storage Cost/ton as is	$7.31	$7.31	$7.31	$7.31	$7.31
If Square Bales are used:					
Number of Bales	511,443	1,022,887	2,045,774	3,068,660	4,091,547
Bale Storage area, sq ft	5,455,396	10,910,792	21,821,584	32,732,376	43,643,168
Bale Storage area, acres	125	250	501	751	1,002
Number of 10-acre Storage sites	13	26	51	76	101
Number of Bales per site	39,342	39,342	40,113	40,377	40,510
Tons stover per site	31,428	31,428	32,045	32,256	32,362
Number of days supply	26.9	13.5	6.9	4.6	3.5
Annual Land/prep cost	$3,269,042	$6,538,084	$13,076,168	$19,614,253	$26,152,337
Annual Equipment cost	$1,172,058	$2,344,115	$4,688,231	$7,032,346	$9,376,462
Total Storage Cost/ton as is	$10.87	$10.87	$10.87	$10.87	$10.87
Total Storage Cost/dry ton	$12.94	$12.94	$12.94	$12.94	$12.94

Table 5. Stover demand and marginal costs, counties, and distance for each plant output level and bale type.

Round Bales (figures in parentheses are for densified case)					
MM annual gallons ethanol	**Stover Demand (dry tons)**	**Marginal Cost ($/ton)**	**Marginal Cost ($/gal ethanol)**	**Marginal Transport Distance (miles)**	**Total Harvest Area (sq miles)**
25	357,787	$56 ($71)	$0.80 ($1.02)	33 (35)	2,337 (2,225)
50	715,574	$65 ($76)	$0.92 ($1.09)	49	4,864
100	1,431,147	$74 ($80)	$1.05 ($1.14)	72	9,766
150	2,146,721	$78 ($82)	$1.12 ($1.18)	101	14,665
200	2,862,295	$84 ($86)	$1.21 ($1.22)	114	19,832 (19,884)

Square Bales (figures in parentheses are for densified case)					
MM annual gallons ethanol	**Stover Demand (dry tons)**	**Marginal Cost ($/ton)**	**Marginal Cost ($/gal ethanol)**	**Marginal Transport Distance (miles)**	**Total Harvest Area (sq miles)**
25	357,787	$50 ($72)	$0.71 ($1.04)	33	1,670
50	715,574	$54 ($76)	$0.77 ($1.09)	48	3,548
100	1,431,147	$56 ($79)	$0.81 ($1.12)	55	7,252
150	2,146,721	$60 ($82)	$0.86 ($1.17)	77	10,820
200	2,862,295	$62 ($84)	$0.89 ($1.20)	101	14,665

Table 6. Summary statistics from Monte Carlo simulation ($/dry ton).

Statistics	**Square-Current**	**Square-NoTill**	**Round-Current**	**Round-NoTill**
Trials	10,000	10,000	10,000	10,000
Mean	52.30	52.21	63.05	62.99
Median	50.08	50.24	62.49	62.60
Standard Deviation	11.52	10.83	9.31	8.50
Variance	132.68	117.38	86.58	72.17
Skewness	5.16	4.93	4.78	3.15
Kurtosis (peakedness)	53.70	52.70	57.82	32.31
Minimum	38.02	38.15	48.18	48.48
Maximum	240.78	244.69	223.97	183.62

Table 7. Rank correlation coefficients between simulated variables and marginal stover cost.

Variables	**Square-Current**	**Square-NoTill**	**Round-Current**	**Round-NoTill**
Bale Moisture Content	0.70	0.71	0.53	0.53
Farmer Participation Rate	-0.27	-0.27	-0.51	-0.48
Stover Collection Efficiency	-0.49	-0.49	-0.47	-0.47

Figure 1. Study area considered for corn stover harvest (United States of America, 2006). Yellow oval denotes conversion facility location.

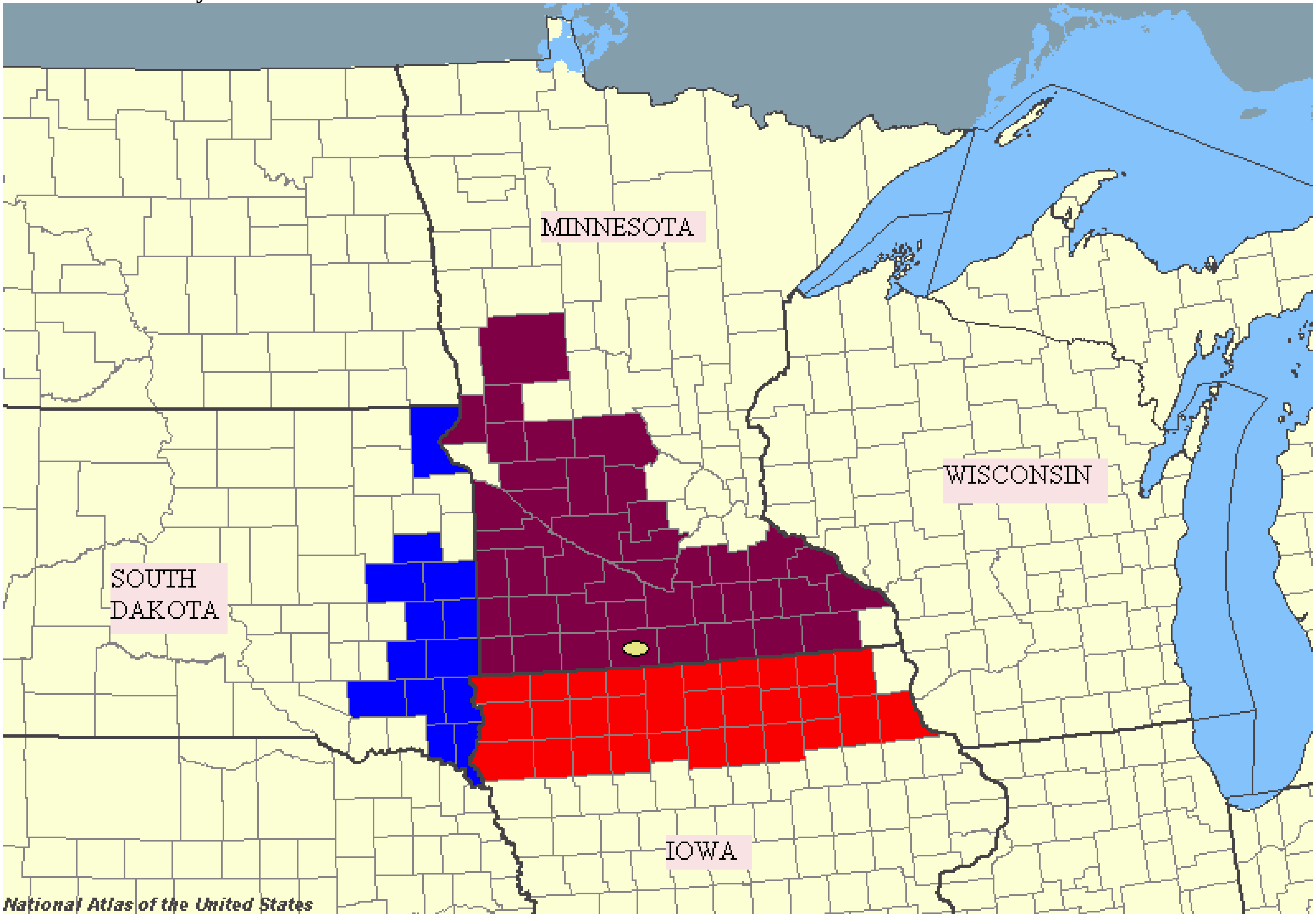

Figure 2. Counties of origin for round-baled stover to supply conversion facility producing 25 million gallons annually (red), 50 (add yellow), 100 (add green), 150 (add blue), and 200 (add purple) (United States of America, 2006). The black oval denotes the location of the conversion facility.

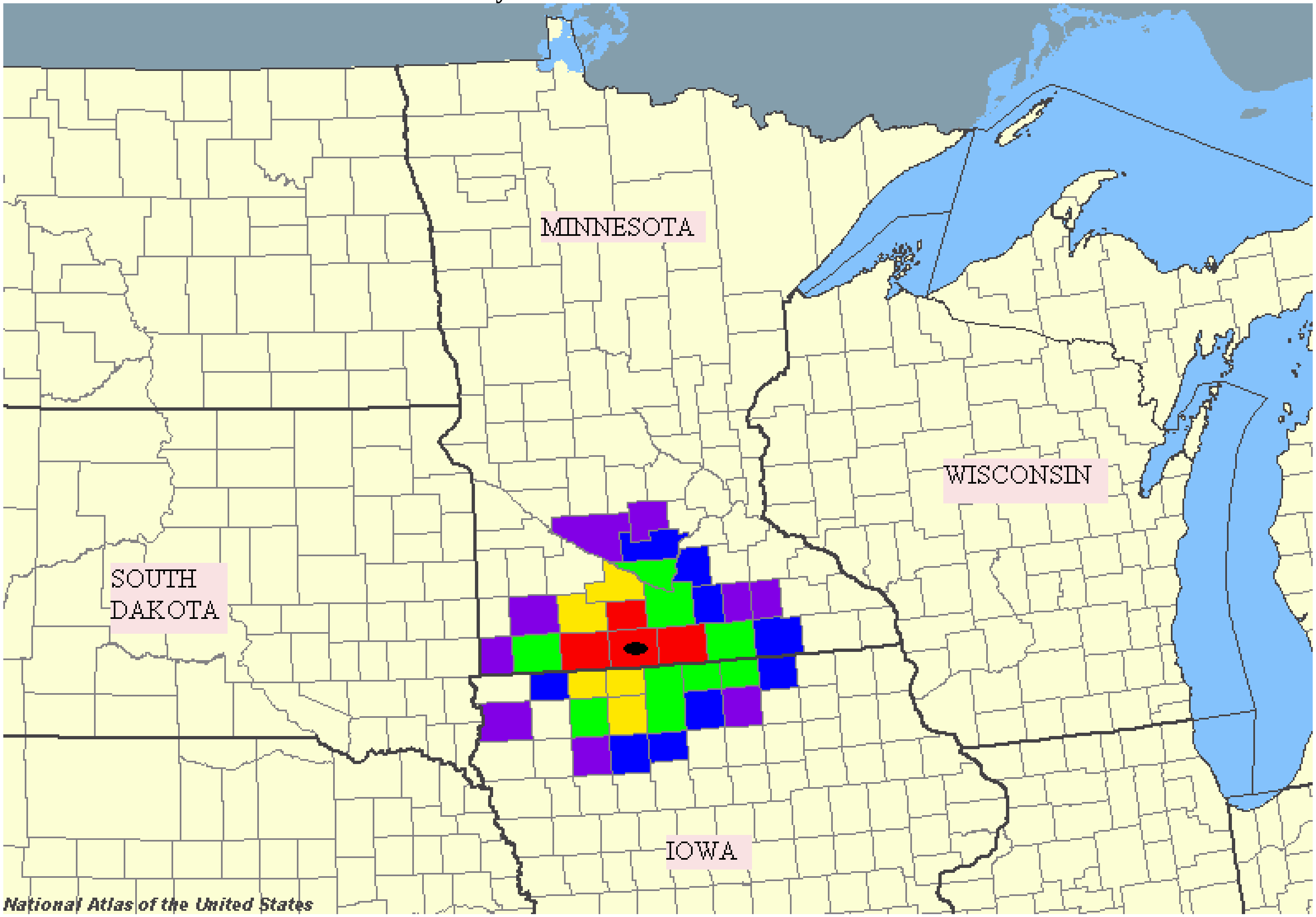

Figure 3. Counties of origin for square-baled stover to supply conversion facility producing 25 million gallons annually (red), 50 (add yellow), 100 (add green), 150 (add blue), and 200 (add purple) (United States of America, 2006). The black oval denotes the location of the conversion facility.

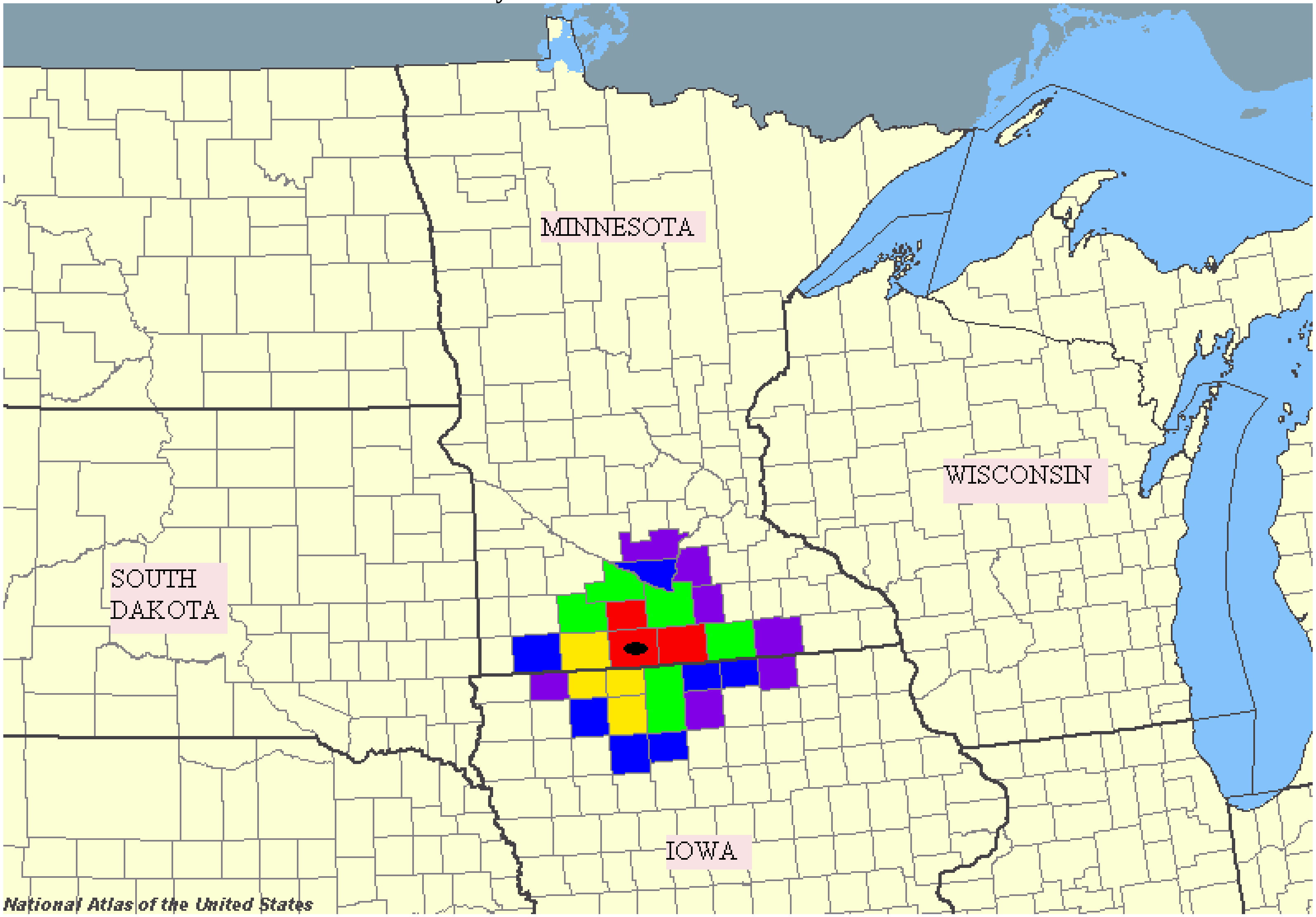

Figure 4. Counties of origin for densified stover harvested as round bales to supply conversion facility producing 25 million gallons annually (red), 50 (add yellow), 100 (add green), 150 (add blue), and 200 (add purple) (United States of America, 2006). The black oval denotes the location of the conversion facility.

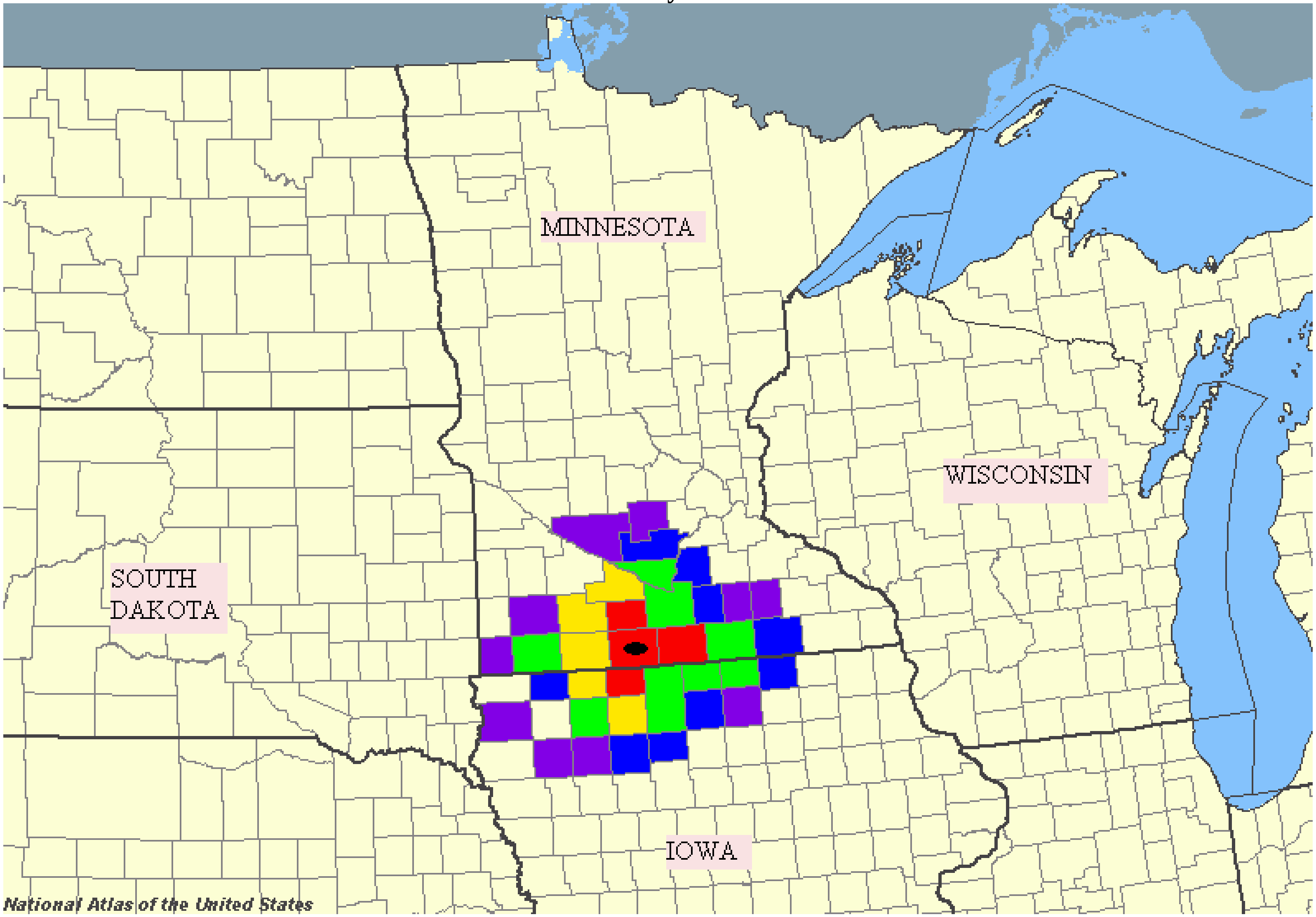

Figure 5. Supply curves for round and square bales of corn stover, dollars per dry ton.

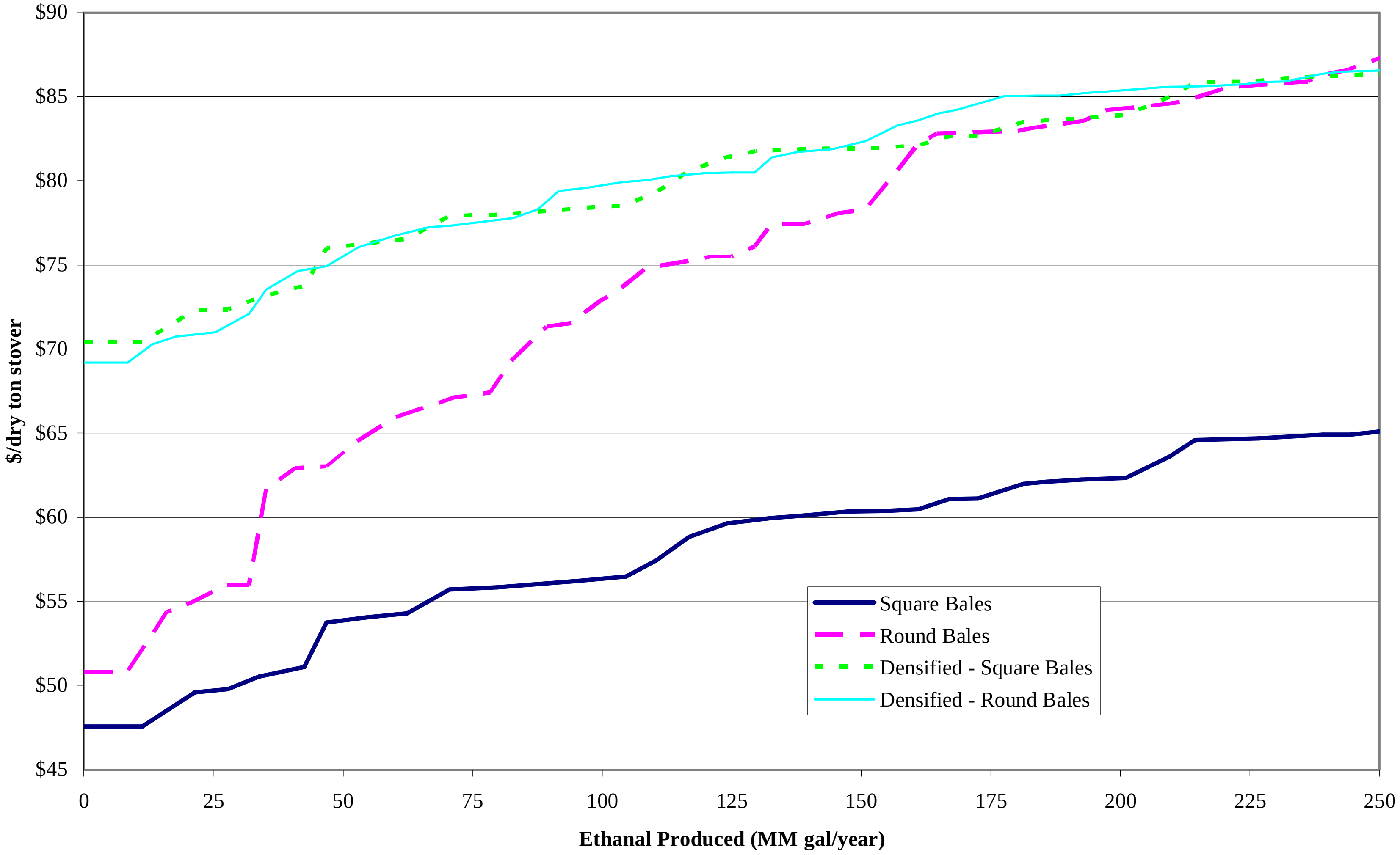

Figure 6. Probability distribution of marginal costs ($/dry ton): current tillage and square-bale method.

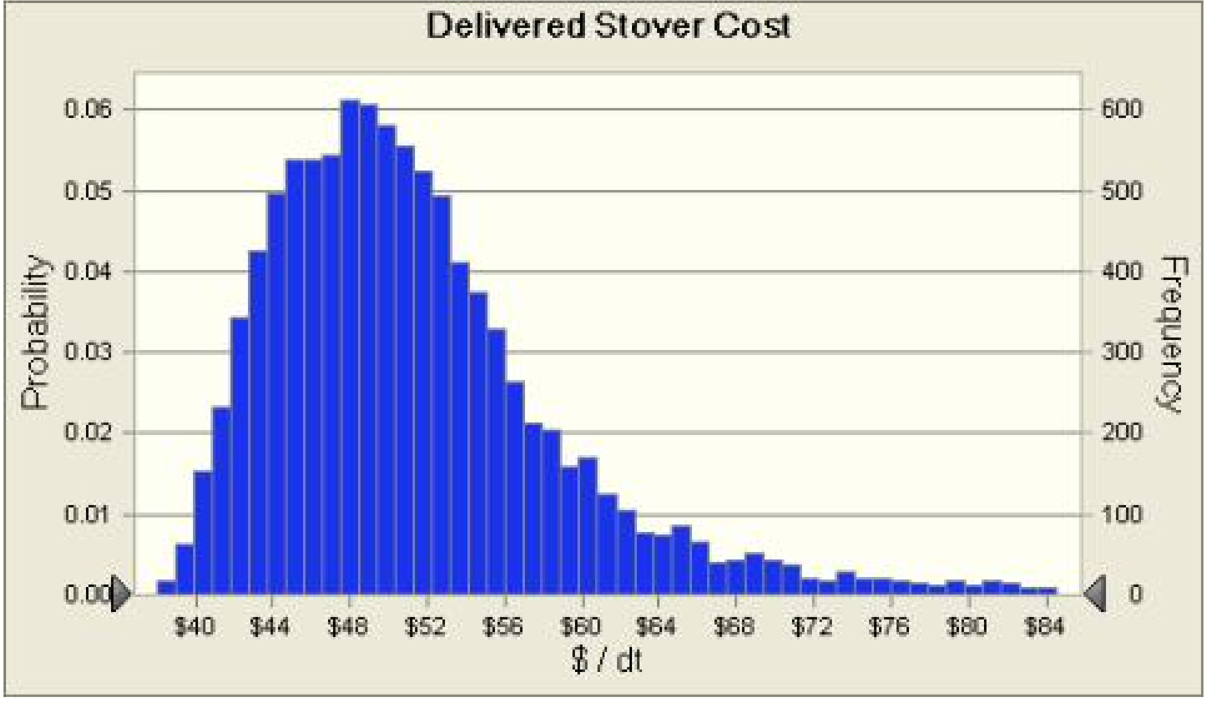

Figure 7. Probability distribution of marginal costs ($/dry ton): no-till and square-bale method.

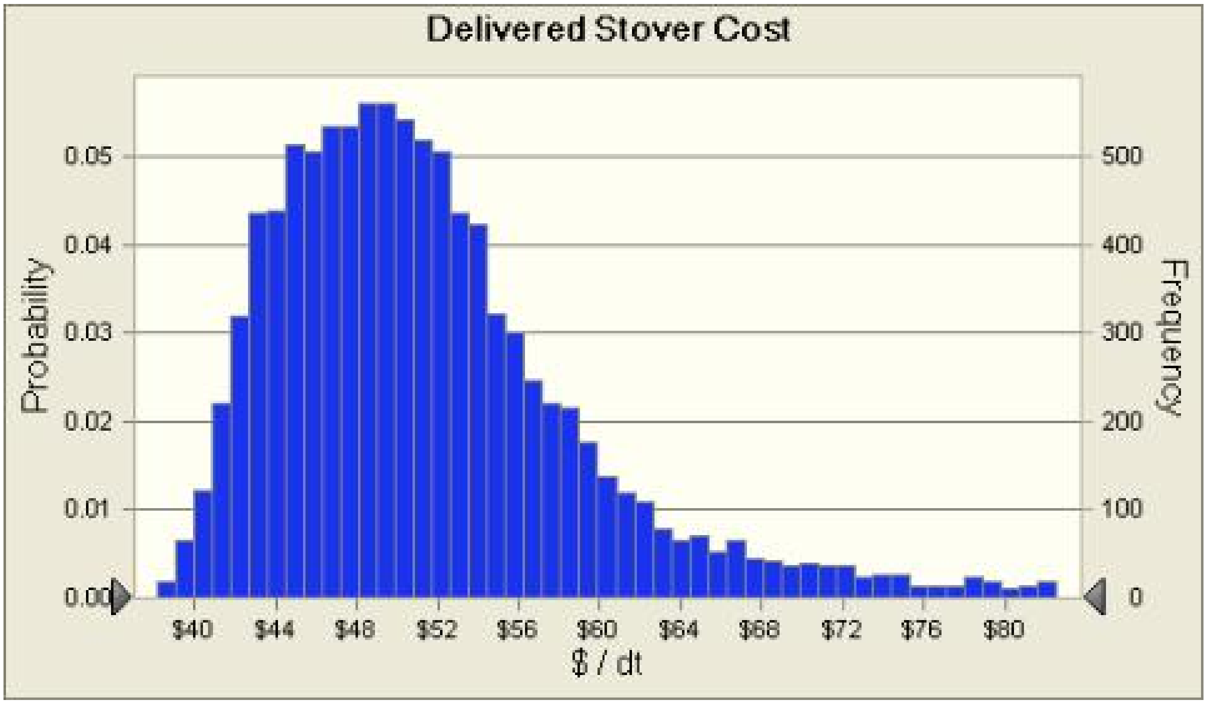

Figure 8. Probability distribution of marginal costs ($/dry ton): current tillage and round-bale method.

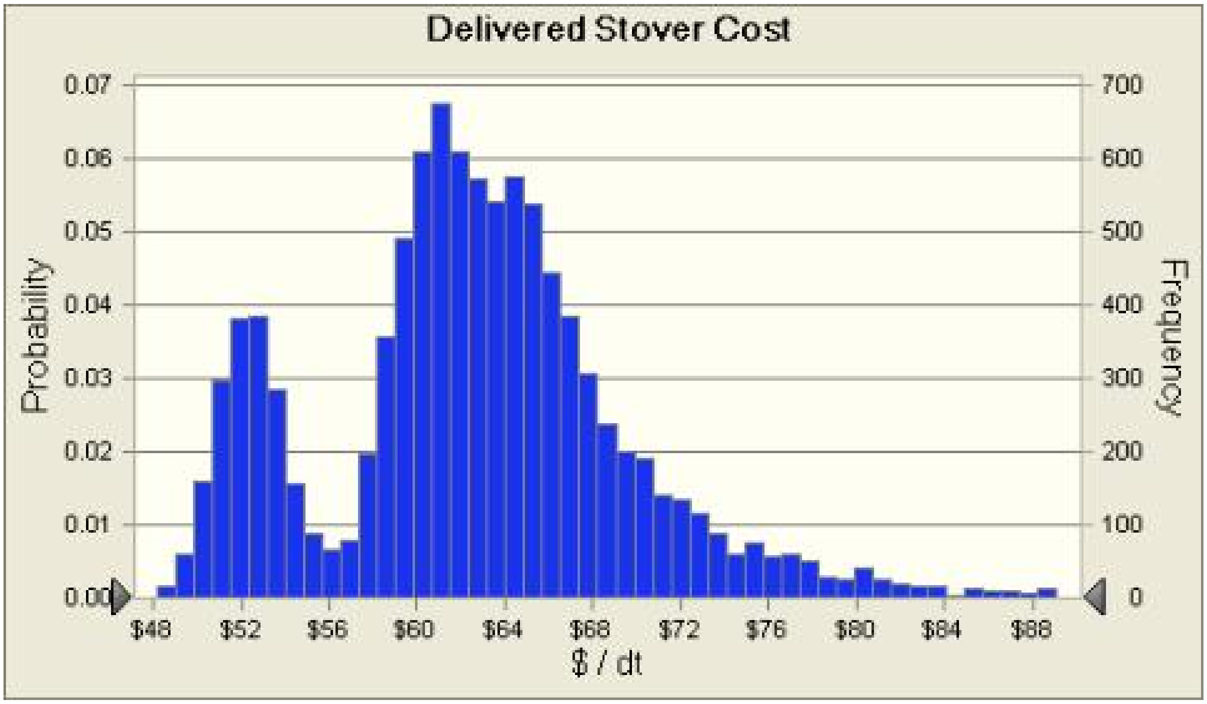

Figure 9. Probability distribution of marginal costs ($/dry ton): no-till and round-bale method.