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Biomass supply schedules for Great Plains delivery points

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ABSTRACT

This study examines the biomass price needed to deliver various amounts of biomass to three delivery points in the Great Plains. We estimate production and delivery costs on the basis of most common custom rates in the area for the various operations. We find that up to a million Mg of corn stover biomass annually could be delivered to each delivery point at prices of \$69–76 Mg^{-1} of dry matter. Switchgrass could be supplied in these quantities only at higher prices around \$80 Mg^{-1}. Differences in crop densities and yields across the three delivery points affect stover supply price by as much as 10%, but have smaller effects on switchgrass supply prices because potential crop densities are higher. The minimum estimated cost and associated supply radius required to provide combustion fuel for combined heat and power at existing grain ethanol plants range from \$64 Mg^{-1}, 16 km, to \$47 Mg^{-1}, 27 km. The minimum cost and associated radius for providing sufficient biomass for a 150 million liter per year cellulosic ethanol plant range from \$66 Mg^{-1}, 35 km to \$72 Mg^{-1}, 55 km.

1. Introduction

Crop residues such as corn stover and dedicated biomass crops such as switchgrass are potential substitutes for fossil fuels, either as direct combustion materials or after conversion to liquid fuels. These sources of biomass have very low energy density and are also available in farm fields at relatively low density, with the result that collection, storage and transportation costs per unit of energy delivered can be quite high ([1–6]). Moreover these costs can rise considerably with increases in the quantity supplied to a given delivery point. Research on densification technology ([7,8,9,10,11]) may ultimately reduce these costs, but meanwhile, investment decisions by biomass users and producers must be based on current technologies. The objective of the present study is to evaluate the current technology supply curves for delivery of various amounts of crop biomass to three points in different agro-ecological zones in the plains.

2. Material and methods

Delivery points considered in this study are at the Nebraska towns of Adams, Wood River and Norfolk (Fig. 1). A corn ethanol plant exists at each delivery point, that could potentially utilize biomass for combustion fuel or for expanded facilities for cellulosic ethanol production. Moreover, the areas around these points are representative of a range of conditions in the Great Plains, in that they differ in cropping density and irrigation. In the vicinity of Wood River (Adams, Buffalo, Hall, counties) most crop production is irrigated, while near Adams (Gage, Johnson, Lancaster and Otoe counties) very little is irrigated, and in the area around Norfolk (Madison, Pierce, Stanton and Wayne Counties) about one-third of crop area is irrigated. Supply areas considered in this study are circular, with the assumption of uniform characteristics corresponding to the average of surrounding counties in the vicinity of the processing plant.

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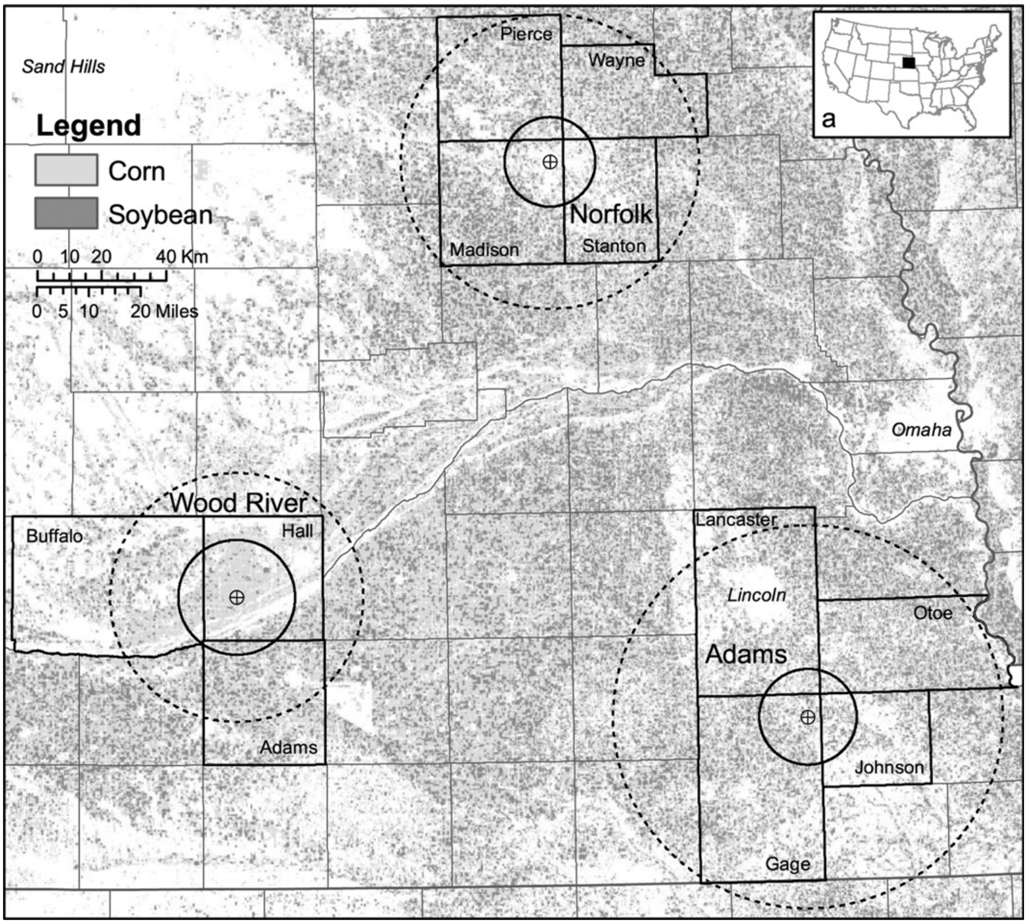

Fig. 1 – Biomass delivery points and supply areas. The smaller circles represent the supply area required to provide switchgrass to meet combustion needs of current grain ethanol plants (amounts vary with plant size). The larger circles represent areas required to provide feedstock for a 150 m liter per year cellulosic ethanol plant (about 450,000 Mg per year). Map source: USDA, National Agricultural Statistics Service, 2008 Nebraska, Kansas and Iowa Cropland Data Layers.

The quantity of biomass required at a point depends upon the nature and size of the facility at the delivery point. For example, a very large cellulosic ethanol plant with 380 million liter per year (mly) capacity would require about 1.15 million Mg^{-1} of biomass per year, whereas a corn ethanol plant of the same capacity using biomass for combined heat and power (CHP) would require about 0.23 million Mg^{-1}. An existing corn ethanol plant is located next to each of the towns in this study, providing a potential market for biomass, either as combustion fuel for CHP technology or for future plant expansion or conversion to produce cellulosic ethanol.

2.1. *Biomass availability*

The primary source of biomass currently available in these areas is corn stover, but switchgrass could be planted on less productive lands now allocated to grass hay or pasture. In our spatial calculations, we calculate average county-level crop densities and corn yields in counties surrounding the delivery point, and assume the distribution of crop areas to be uniform within the supply radiuses.

Corn stover production is estimated at one-half of the average grain production (dry matter basis) in the area over 2006, 2007 and 2008. An unresolved issue is the fraction of the stover that can be harvested without adverse impacts on future soil productivity. Gallagher et al. [12], Gallagher et al. [13], and Sheehan [14] calculated crop residue-erosion tradeoffs for different land types across the Corn Belt. They estimated maximum stover removal rates for maintenance of tolerable soil loss due to erosion based on these tradeoffs. Blanco-Canqui and Lal [15] observe that “The few studies conducted to establish the threshold levels of crop residue removal for alternative uses, specifically in the U.S. Corn Belt region, indicate that about 30%–50% of the total stover produced can be removed without causing severe adverse impacts on soil (Lindstrom et al., 1979; Nelson, 2002; Kim and Dale, 2004; Graham et al., 2007).” They conclude that “…impacts of residue removal on soil physical properties and crop yields are inconsistent, even with complete crop residue removal. In some soils, crop yields vary more from year to year due to weather fluctuations, which make the determination of the effects of residue removal difficult (Linden et al., 2000).” Given this lack of scientific clarity, we assume for this study a conservative harvesting strategy consisting of the removal of 50% of stover on 50% of corn area, for an average harvest of 25% of available stover biomass. This harvest rate is more conservative than average harvest rates calculated or assumed by Sheehan [14] (an average of 40% of available stover), Gallagher et al. [12] (100% of stover on 60% of acres), Gallagher et al. [13] (100% of stover on class I and II lands) in the western Corn Belt, and by Brechbill and Tyner [4] (38%, 52%, and 70%) in Indiana. It appears to correspond closely to Poet's corn residue harvest plan (http://www.poet.com/discovery/releases/showRelease.asp?id=274, accessed July 1, 2011).

Much less is known about potential production of switchgrass biomass, because USDA-NASS statistics are not available for the crop. Instead, for yields we use the average harvest results obtained in recent research on the switchgrass fields of ten collaborating producers in the Great Plains over the years 2000–2005 [16], which on a dry matter (DM) basis was approximately 6.7 $\mathrm{Mg^{-1}\ ha^{-1}}$. We calculate the potential area of switchgrass production in each region as the density of idle cropland, pastureland and hay [17]. For spatial calculations, we assume a uniform distribution of these areas within the supply region, as was also assumed for corn stover.

2.2. *Structure of aggregate supply functions*

Costs of delivery of biomass to a given point consist of production costs at the farm plus transportation costs. Given our assumption that acreage, yield and harvest practices are homogeneously distributed around the delivery point, additional deliveries come from an expanding circle around the delivery point, with transportation cost determined by the radial distance to the point of production [16]. Given this assumption, total cost of delivering q_k^i $\mathrm{Mg^{-1}}$ of feedstock i (i = stover, switchgrass) to point k (k = Adams, Wood River, Norfolk) can be expressed as[1]

$$TC_k^i = a_k^i q_k^i + b q_k^i + \frac{2c}{3\sqrt{\pi d_k^i}}\left(q_k^i\right)^{3/2} \tag{1}$$

where a_k^i represents on-farm costs per Mg, b represents loading, unloading and stacking costs per Mg of any feedstock, c represents transportation cost, in $\$\ \mathrm{Mg^{-1}\ km^{-1}}$ for any feedstock, and d_k^i represents harvest density in $\mathrm{Mg\ km^{-2}}$.

Based on this expression the marginal cost of quantities delivered (*i.e.*, the inverse supply function) can be expressed as

$$MC_k^i = a_k^i + b + \frac{c}{\sqrt{\pi d_k^i}}\sqrt{q_k^i}. \tag{2}$$

To obtain the supply function for the quantity of feedstock i in region k, we set price at marginal cost and solve this equation for quantity delivered. This supply function is thus quadratic in prices:

$$q_k^i = \begin{cases} \frac{\pi d_k^i}{c^2}\left[p^2 - 2\left(a_k^i + b\right)p + \left(a_k^i + b\right)^2\right], & \text{if } p > \left(a_k^i + b\right), \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

The aggregate supply function for delivery of all biomass feedstocks to a given point is the horizontal sum of these individual feedstock supplies.

Previous studies ([12–14]) have calculated supply functions based on average cost per Mg rather than marginal cost per Mg as we use here. Either price schedule may be relevant, depending on market structure. Marginal cost schedules would be relevant for a buyer who posts a CIF price to be paid to any interested seller for product delivered to a receiving point. Average cost schedules are relevant for a buyer with trucks and equipment who pays the same farm gate FOB price to each seller for biomass picked up at the edge of the field. We do not have a theory to predict what type of market structure will emerge, so we choose to report marginal cost schedules simply because CIF pricing is the standard practice for grain and livestock delivery points in the Midwest. We also calculated average cost schedules for the empirical cases considered, but do not report them because they look very much like the marginal cost schedules (average costs are 3–5% below marginal costs for stover supply, 1–2% below marginal costs for switchgrass supply).

We estimate costs of production, harvesting and transportation of biomass based on operations required using conventional technology. Our cost estimates are based on custom rates for these operations as reported from survey data in Nebraska [18], reported in Table 1. This method is in contrast to other biomass supply studies, which have used engineering cost approaches to estimate the cost of various operations. We isolate the fuel component of these costs by relying on engineering estimates of the amount of fuel required for each operation [19], multiplied by current diesel price. This allows adjustment of estimated biomass supply costs as fuel prices vary in the future.

3. Results

Of the costs identified in the section above, loading/stacking costs (b) and transportation costs (c) are common to both corn stover and switchgrass, because we assume that both feedstocks are handled in conventional large round bales. Given that we have no custom rate data for loading, unloading and stacking bales at the destination, we utilize the Kumar and Sokhansanj estimate [20] of \$1.77 $\mathrm{Mg^{-1}}$ for loading and \$2.34 $\mathrm{Mg^{-1}}$ for unloading and stacking, yielding the estimate $b = \$4.11\ \mathrm{Mg^{-1}}$. We estimate the diesel fuel component for this operation at 0.034 l $\mathrm{Mg^{-1}}$.

We estimate transportation cost based on the reported custom rate (Table 1) of \$2.17 per loaded km for semi-trailer trucks that hold 26 bales weighing 0.6 Mg (DM), or $c = \$0.168\ \mathrm{Mg^{-1}\ km^{-1}}$. The diesel fuel component within this rate, based on fuel consumption of 3.8 km $\mathrm{l^{-1}}$, is 0.06 l $\mathrm{Mg^{-1}\ km^{-1}}$. Remaining cost components are on-farm costs (a_k^i) and harvest density (d_k^i), which vary by source and region, as detailed next.

3.1. *Corn stover: harvest densities and on-farm costs*

The average stover harvest densities (DM) during 2006–2008, d_k^{stover}, around Adams, Wood River and Norfolk were 119, 287 and 204 $\mathrm{Mg\ km^{-2}}$ respectively, as calculated in Table 2. Here we assume that stover yield equals corn grain yield, that

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[1] Quantity harvested within radius R is $q = \pi d R^2$. Cost of transporting all production at radius r is $d(2\pi r)rc$. Integrating from $r = 0$ to $r = R$, $C = (2/3)cd\pi R^3$. Substituting q for R, $C(R) = (2/3)c(d\pi)^{-1/2}q^{3/2}$.

Table 1 – Most common custom rates for biomass harvest operations.

Operation	Unit	Custom rate per unit ($)[a]	Liters diesel per unit[b]
Stalk shredding	ha	21.98	4.21
Stalk raking	ha	12.35	2.34
Swathing hay with crushing	ha	29.64	5.80
Baling, large round w/netwrap (721 kg switchgrass, 606 kg stover bale^{-1})	bale	12.00	1.51
Moving bales to edge of field	bale	2.00	0.757
Hauling round bales (13.6 Mg load)	loaded km	2.17	0.294

a Source: Jose (2010).
b Source: Hanna (2001).

moisture content of both grain and stover is 15%, and that half the stover is removed from half of the corn acreage each year.

On-farm costs, a_k^{stover}, summarized in Table 3, are based on custom rates for various field operations as reported in Table 1, and on harvest densities shown in Table 2. These operations use current commercial technology for large round bales, covered with bale wrap and moved to the edge of the field for later retrieval. An unresolved empirical issue is the compensation that farmers will demand in exchange for extra traffic on their fields, potential losses of soil carbon, etc. In the absence of any empirical information about this, we have arbitrarily adopted a producer contract payment of $7.48 Mg^{-1}DM, as argued by Morey et al. (10), plus a charge to replace lost nutrients (next paragraph). This payment scheme results in estimated per hectare contract payments of $25.66, $35.64, and $30.28 for the areas around Adams, Wood River ad Norfolk, respectively.

As noted above, the impact of stover removal on long-term yields remains controversial. Varvel et al. [21] report that removal of 50% of corn stover in Nebraska results in a yield reduction of about 5%, while Moebius-Clune et al. [22] report a reduction of about 8% in New York. Blanco-Canqui et al. [15] report mixed results. Similarly, an earlier authoritative review by Wilhelm et al. [23] revealed that many experiments have showed no yield reduction from stover removal, and they concluded that the inconsistency of results is probably explained by differences in soil type, weather, tillage, etc. D. Walters (personal communication, 2009) and others have measured nutrients removed from the field with stover harvest, which are approximately 18 kg of N Mg^{-1} and 2.0 kg of elemental phosphorus (P) plus potash which is at present not limiting in most soils of the Great Plains. For this study we simply assume that replacement of these nutrients would compensate for future yield losses. Current materials and application costs for these nutrients total $18.77 Mg^{-1}.

Table 2 – Stover harvest densities around three delivery points.

	Units	Adams	Wood River	Norfolk
Avg corn density, 2006–08	ha km^{-2}	24.2	42.1	35.2
Avg corn grain yield, 2006–08	Mg ha^{-1}	8.08	11.22	9.53
DM stover produced/ha corn[a]	Mg ha^{-1}	6.86	9.53	8.10
DM stover harvested/ha corn	Mg ha^{-1}	3.43	4.76	4.05
d = harvest density[b]	Mg km^{-2}	119	287	204
Bales per ha harvested	Bales/ha	5.60	7.78	6.61

a (Corn yield)*(0.85 DM).
b (Mg DM prod ha^{-1})*(ha km^{-2})/4.

Total on-farm costs for harvesting and collecting stover thus range from $56.30 Mg^{-1} in the Wood River area to $59.11 Mg^{-1} in the Adams area (Table 3). Brechbill and Tyner [4] budget the on-farm harvest and collection cost for corn stover (converted to dry tons) at only $30.34–34.08 Mg^{-1}, Sokhansanj et al. [2] at $40.15 Mg^{-1}, and Lazarus [24] at $55 Mg^{-1} (The first two estimate baling costs to be quite low, about half the most common custom rate prevailing in Nebraska.)

Given our estimates of cost parameters described above, stover supply schedules calculated from Equation (3) for the three delivery points are graphed in Fig. 2. Here we have budgeted for production of an additional 5% above delivery requirements to account for average storage losses between the time of harvest and use [10]. Harvest density is the primary factor distinguishing the levels of the three stover supply curves. Delivery of 1 million Mg^{-1} in the Adams area involves about $13 Mg^{-1} of transportation costs at the extensive margin, whereas at Wood River, marginal transportation cost for the millionth Mg is only about $7 Mg^{-1}.

Table 3 – On-farm costs per Mg (DM) of stover[a].

	Adams	Wood River	Norfolk
Stalk shredding	6.40	4.61	5.43
Raking	3.60	2.59	3.05
Baling, large round w/netwrap	19.58	19.58	19.58
Moving bales to edge of farm	3.26	3.26	3.26
Nutrient replacement[b]	18.77	18.77	18.77
Producer contract	7.49	7.49	7.49
Total	59.11	56.30	57.58

a Calculated from Tables 1 and 2.
b 7.3 kg N, 0.8 kg P.

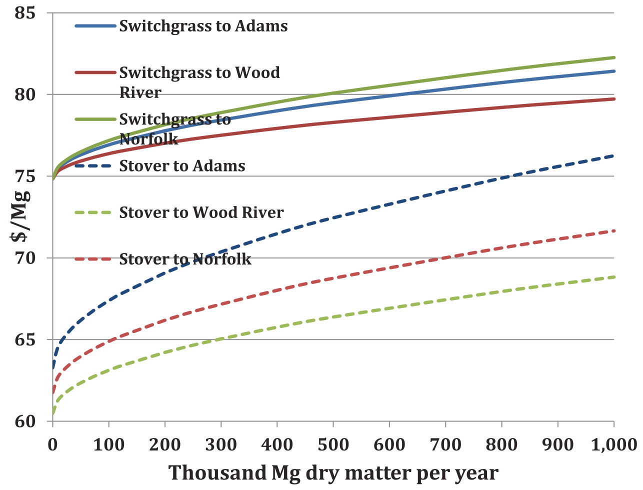

Fig. 2 – Supply schedules for delivery of corn stover and switchgrass to three delivery points in the Great Plains.

3.2. *Switchgrass: harvest densities and on-farm costs*

We assume that land around the delivery points that could be converted to switchgrass production includes cropland that is either idle, used only for pasture, or used for hay production (other than alfalfa), plus land in permanent pastures. This comprises from 25% of the area in the Adams region to 34% of the area around Wood River (Table 4). We estimate the average switchgrass dry matter yield after the establishment year to be 6.7 Mg^{-1} ha^{-1}, approximately the average yield obtained in ten on-farm, commercial scale trials in the Great Plains during 2001–2005 [16,25]. The density of potential switchgrass harvest at this yield level ranges from 155 to 355 Mg^{-1} km^{-2}, 25–75% higher than the harvest densities for corn stover.

In addition to harvest costs, production costs for switchgrass include land rent (unnecessary for harvesting stover as a corn crop residual) and an expected establishment cost of \$555 ha^{-1} that includes an allowance for re-seeding (expected 25% of the time) (Table 5). Our estimate of land rent is based on average reported cash rent for hay land in this region in 2010 [26]. This rental rate will likely be driven up in the future, both by higher grain prices (higher opportunity cost of the land) and perhaps by competition from biomass-using facilities. We amortize establishment expense over 10 years of production, using an 8% amortization rate (capital recovery factor = 0.15), resulting in an annualized establishment cost of \$83.32 ha^{-1}.

Table 4 – Switchgrass harvest densities around three delivery points.

	Units	Adams	Wood River	Norfolk
Avg acreage density, 2006–08	ha km^{-2}	29	53	23
d = harvest density (DM)	Mg km^{-2}	196	355	155

During production years, fertilization is the only expense other than harvesting costs, and the two together total \$257 ha^{-1}. The total of farm-level costs is \$476 ha^{-1}, or \$70 Mg^{-1} given a yield of 6.74 Mg ha^{-1} (3 t a^{-1}) during production years. This is our estimate of the $a_k^{\text{switchgrass}}$ parameter for all three regions, which, when combined with the \$4.13 Mg^{-1} loading/unloading cost, puts the intercepts for the switchgrass supply curves at \$74.83 Mg^{-1}. This is quite expensive relative to the cost of corn stover, even above the prices needed to supply a full one million tons of stover biomass to two of the three delivery points (Fig. 2). It thus appears from this analysis that using current technology, switchgrass is not a competitive source of biomass in this region, even when planted on more marginal soils.

The on-farm trials in the study by Perrin et al. [16] found farm gate costs to be \$49 per ton during 2000–2005, about \$15 lower than costs we estimate here. Most of this difference is accounted for by custom harvesting costs that are currently about \$11/t higher than costs reported by cooperating farmers in the earlier study. Previous estimates of comparable on-farm switchgrass costs in the central regions of the U.S. have varied markedly. Brechbill and Tyner [4] estimate them at \$42.48–44.76 Mg^{-1}, Epplin [27] at \$29.35, Bangsund et al. [28] at \$67.02, Sokhansanj et al. [8] at \$37.73, Lazarus [24] at \$68 and de la Torre Ugarte et al. [29] at \$22.97 not including land rent.

Using our estimated parameters and Equation (2), supplies of biomass from switchgrass to the three delivery points are also depicted in Fig. 2. As with corn stover, we have budgeted for the production of an additional 5% of switchgrass to account for average storage losses before delivery. Due to the higher potential density of production, the supply curves for switchgrass rise much less steeply than those for corn stover.

The total supply curves for biomass including both stover and switchgrass could be calculated as the horizontal summations of the respective curves in Fig. 2, but since supplies of stover exceed one million Mg at the price level needed to stimulate the first units of switchgrass, we do not construct those graphs for this study.

4. Discussion

Supplies of biomass might be used in at least three types of facilities at delivery points such as these: for co-firing with coal or direct firing in electricity generating plants, for use as fuel for CHP (combined heat and power) in corn ethanol plants or other facilities, or as feedstock for cellulosic ethanol plants. Helius Energy's biomass power plant project in England, for example, proposes to use 850,000 tons of biomass per year for a 100 MW power plant (http://www.heliusenergy.com/). USDA's roadmap for meeting biofuel goals [30] calls for the construction of 226 biorefineries in this (Central East) region, with an average capacity of 150 m liters (40 million gallons) per year. A cellulosic ethanol plant of this size would require about 450,000 Mg of stover or switchgrass per year (calculated at 275 l of ethanol per Mg of biomass). This amount of stover could be delivered to the three points at prices of \$72.46 Mg^{-1} at Adams, \$66.38 at Wood River, and \$68,75 at Norfolk, whereas a price nearly 10–15% higher would be necessary to provide the required amount of switchgrass (Table 6). The

Table 5 – On-farm production costs of switchgrass for biomass.

Operation	Cost of operation		Materials cost[c]			Total cost
	Custom rate[a]	Diesel fuel l ha^{-1} [b]	Material: qty ha^{-1}	Price per unit	Total materials	
Establishment costs per ha						
Disk	24.70	7.95				24.70
Seedbed conditioning	29.64	8.41				29.64
Sow seed	37.05	6.54	Seed: 6.7 kg	16.54	110.80	147.85
Spray chemicals	14.82	0.93	Paramount: 0.58 l	135.14	78.38	93.20
			Atrazine: 2.3 l	5.68	13.11	13.11
Land rent[f]	135.85					135.85
Total	242.06	23.84			202.29	444.35
Re-seeding allowance[d]	60.52	5.96			50.57	111.09
Total establishment	302.58	29.80			252.86	555.44
Annualized establishment cost[e]	45.69	4.47			15.56	83.32
Annual production costs ha^{-1}						
N fertilizer, applied		1.40	78 kg N ha^{1}	0.94815	73.96	73.96
Swath/condition	29.64	5.14				29.64
Baling, large round w/netwrap[g]	131.72	16.45				131.72
Moving bales to edge of farm[g]	21.80	8.23				21.80
Land rent[f]	135.85					135.85
Total production year costs	319.01	31.23			73.96	392.97
Total annual & establ. costs	363.33	35.70			45.66	476.28
Per Mg DM, at 6.74 Mg DM ha^{-1}	\$53.94	\$5.30			\$6.78	\$70.70

a From Jose, 2010.
b From Hanna, 2001.
c From Klein, 2010.
d 25% of initial establishment cost.
e Amortized over 10 years at 8% discount rate, capital recovery factor = 0.15.
f Average cash rent for hay land in 2010 (Johnson et al., 2010).
g At 10.9 bales ha^{-1}.

calculated distances from the centers to the edges of the 450,000 Mg supply areas are 55, 35 and 42 km, respectively.

The current corn ethanol plants at these towns have capacities of 190 mly, 414 mgy and 150 mgy, respectively. At 4.86 lbs of biomass required for heat and power for each gallon of corn ethanol produced, the annual amounts of biomass needed for CHP at these plants are 84,000, 185,000 and 67,000 Mg y^{-1} (Table 6). These quantities would require stover prices of \$67 Mg^{-1} at Adams, \$64 at Wood River and Norfolk. Prices necessary to obtain switchgrass in those quantities would need to be about 20% higher.

Several considerations would lead to shifts in these biomass supply curves, among them being changes in diesel prices, government programs, and different yields. Diesel requirements other than trucking total about 5.8 l Mg^{-1} for both stover and switchgrass. At \$0.80 l^{-1}, fuel cost is \$4.60 Mg^{-1} so a doubling of diesel price would shift the supply curve intercepts up by \$4.60 Mg^{-1}, which is about 6% of the switchgrass intercept and 7% of that for stover. Similarly, at \$0.80 l^{-1}, diesel comprises about 10% of the transportation costs, so the slopes of the supply curves would increase about 10% if diesel price were to double to \$1.60 l^{-1}.

USDA's Biomass Crop Assistance Program (BCAP) promised to match buyers' payments to farmers, which implies that the price at which producers would be willing to provide various quantities could be as little as half the prices shown

Table 6 – Supply price and radius for supplying alternative biomass facilities.

Supply for	Source	Result	Adams	Wood River	Norfolk
150 mly cellulosic ethanol plant		Mg required	453,500	453,500	453,500
	Stover	Radius in km	54.8	35.2	41.8
		Price per Mg	\$72.46	\$66.38	\$68.75
	Switchgrass	Radius in km	27.8	20.6	31.3
		Price per Mg	\$79.49	\$78.29	\$80.08
CHP for existing corn ethanol plant		Mg required	84,127	185,079	67,302
	Stover	Radius in km	23.6	22.5	16.1
		Price per Mg	\$67.23	\$64.25	\$64.45
	Switchgrass	Radius in km	12.0	13.2	12.1
		Price per Mg	\$79.49	\$78.29	\$76.85

on these supply schedules. However, BCAP payments are limited statutorily to two years, so it is unlikely that producers would be willing to supply switchgrass quantities at half the prices shown in Fig. 2, because those costs are based on a 10-year planning horizon. Supply curves for corn stover, however, might be lowered by nearly 50% by BCAP initially, though costs would rise as individual producers exhaust their two years of eligibility for the subsidy. At this writing, however, it appears that the BCAP program will not continue to be funded, so these particular adjustments are probably irrelevant.

Higher per acre yields for either biomass source would lower these supply curves, but not proportionately because a relatively small fraction of supply cost is fixed with respect to yield per acre. In the case of switchgrass, for example, only the establishment cost and the cost for swathing are fixed with respect to yield, and together they comprise only about 25% of the cost of putting a ton of switchgrass on a truck for transportation to a delivery point. The remaining 75% of costs are incurred on a per ton basis, and would therefore not be affected by yield. Thus a given percentage increase in yield per acre would reduce the supply costs by only 25% of that percentage. For example, a costless increase in switchgrass yields of 100%, from 6.74 to 13.5 Mg ha^{-1}, would reduce the intercept of the supply curve by only 25%, from \$75 to \$60 Mg^{-1} A costless yield increase of nearly this magnitude would be necessary to make switchgrass competitive with corn stover as a biomass source in this region.

In addition to these considerations, it is possible that producers would undervalue the \$18.77 Mg^{-1} worth of crop nutrients removed with each ton of corn stover, or that they would be willing to accept less than \$7.50 Mg^{-1} we have budgeted for the nuisance and risks associated with stover harvest. Thus the stover supply curves could shift downward by as much as \$26 Mg^{-1}, with intercepts of about \$35 Mg^{-1} rather than \$62, and the price required to supply one million tons would fall to the range of \$40–50 Mg^{-1}.

5. Conclusions

This study estimates that up to one million Mg of corn stover biomass annually could be delivered to points in the Great Plains at prices of \$68–76 Mg^{-1} of dry matter. Switchgrass, on the other hand, would not be supplied in these quantities at any price less than about \$80 Mg^{-1}. Differences in acreage densities and yields across the three delivery points considered affect stover supply price by as much as 10%, but have little affect on switchgrass supply prices. The amount of biomass required at the delivery point does have an impact on prices required, especially for stover, with small amounts of stover available at about \$65 Mg^{-1}, but a price of \$68-76 would be required to supply a million or more Mg^{-1} y^{-1}.

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