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Supply and Social Cost Estimates for Biomass from Crop Residues in the United States ⋆

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Abstract. The components of social costs included in the supply analysis are cash outlays and opportunity costs associated with harvest and alternative residue uses, potential environmental damage that is avoided by excluding unsuitable land, and costs in moving residues from farms to processing plants. Regional estimates account for the growing conditions and crops of the main agricultural areas of the United States. Estimates include the main U.S. field crops with potential for residue harvest: corn, wheat, sorghum, oats, barley, rice and cane sugar. The potential contribution of residues to U.S. energy needs is discussed.

Key words: biomass supply, crop residues, renewable fuels, sustainable land use, United States agriculture

JEL classifications: Q42, Q21

1. Introduction

Industrial processes for converting biomass into fuel and chemicals now appear on the not-too-distant horizon (Committee on Biobased Industrial Products 2000). Further, some estimates suggest that the physical volume of crop residues compares favorably to other forms of potentially low-cost biomass in the U.S. (Spelman 1994). But there are concerns about competitiveness, sustainability and adequacy of the resource base for biofuels (California Energy Commission 1999). Further, the economic analysis of residue supply as a component of the resource base for the emerging biomass fuel industry is incomplete. Evaluation for public policy requires a resource supply curve that includes both private and social costs. The challenge is

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that markets for crop residues do not exist because processing technology has not emerged in the marketplace. So observed supplies and market prices cannot provide the base for estimation. The residue supply analyses of this paper use productivity and opportunity cost calculations for private costs and exclusion criteria that ensure sustainable land use for internalized social costs. The estimates span major crops and agricultural regions of the United States, taking into account local variation in cost-determining factors such as residue yield, competition from alternative uses, and geographic density of residues. Further, residues are included in supply only if harvest avoids soil erosion, so social supply curves approximate farmers' decisions under a government policy of sustainable land use.

Subsequent sections of the paper look at the residue supply curves for major United States crops. First, methodology is reviewed. Then cost and supply estimates are presented for the major crop producing regions of the United States. The results suggest that crop residues will provide a moderate amount of the U.S. fuel supply when biomass energy technologies are fully developed and adopted.

2. Methodology

Three components of marginal social costs are included in the supply analysis. First, the cash outlays and opportunity costs associated with harvest or farm use of residues are borne by farmers. Second, land is excluded when residue harvest could cause environmental damage; so the environmental cost of the included supply is negligible. Third, society incurs costs in moving residues from the farm to the processing plant.[1]

2.1. FARM SUPPLY

Entry-point supply estimation is useful at the farm level because producer participation in residue harvest is the main supply adjustment. Individual firms or local supply areas are sorted with low-cost producers first and high-cost producers last. The capacity that corresponds to a particular entry price is included in supply when costs are covered. Elsewhere, entry point supply analysis is used for analysis of the supply of transport services in international trade (Shimojo 1979); and producer participation decisions in Government agriculture programs (Hoag and Holloway 1991; Perry et al. 1989).

Two types of economic information are developed for each producer or local supply area. First, the height of the local supply function is identified with cost calculations. Second, a residue balance sheet identifies the output that is available at the cost threshold. Then firms or groups of firms with particular types of outputs are ordered from low-cost to high-cost and aggregated for regional estimates. All cost, output, and feed estimates are developed with county data since agronomic conditions are uniform at this level. Also, data from 1997 forms the baseline because the most recent Census of Agriculture can supplement the annual data from the U.S. Department of Agriculture. County data is used to uncover the effects of variation in residue yield, density and forage requirements on cost and supply.[2]

2.2. CASH OUTLAYS AND OPPORTUNITY COSTS FOR PRODUCERS

The farm-level costs included in estimations are direct harvest costs, the opportunity costs of leaving residues on the soil for fertilizer value, the opportunity cost of using the residue as feed in major livestock areas, and the opportunity cost of using land for wildlife habitat in one major waterfowl flyway.

A general harvest cost function was developed by noticing that some costs are constant on a per acre basis while others are constant on a per unit output basis. The same cost parameters were used for all counties and crops; however, the residue yield and fertilizer replacement rate vary across crops and counties. Direct harvest costs are approximated by machinery replacement and operating costs for harvesting hay in large round bales. The cost estimates allow for three operations: chopping, baling, and on-farm transportation. Field operation costs for chopping and baling are based on estimates from the Society for Agricultural Engineers. Capital replacement cost estimates were provided by Cross and Perry (1995). Lazarus (1997) adapted these cost studies for 1997 conditions. First, estimates for fixed costs are used as reported. Similarly, the reported operating expenses, \$1.47/acre for chopping and \$4.63/acre for bailing, are also used. Reported labor requirements and the local farm wage are important components of the operating expense estimates.[3] The chop and bale costs are all fixed on a per acre basis. The cost of moving the bales to a convenient site for on-farm storage is taken from Duffy and Judd (1994). The farm haul costs are fixed on a per-ton basis.

Indirect fertilizer costs account for the additional needs when residues are harvested. Unused residues provide some phosphorous, potassium, and nitrogen when left for the subsequent crop. Nutrient content tables for the residues of major crops (corn, sorghum, barley, oats, wheat, rice, bagasse) are available (Bath et al.). These tables include direct estimates of phosphorous(P), potassium(K) and nitrogen(N). The N estimate was developed using a protein conversion factor from Russell (1993). The costs of replacing fertilizer associated with residue harvest in 1997 are: \$6.466/ton for corn, \$4.988/ton for wheat, \$5.916/ton for sorghum, \$7.491/ton for barley, \$7.858/ton for oats, \$5.42/ton for rice, and \$3.95/ton for sugarcane bagasse. These costs vary because the fertilizer and nutrient content vary. For crops of the Midwest, the fertilizer replacement costs vary about 50% from wheat to oats.

A harvest cost function that holds for all crops and counties in 1997 depends on the amount of residue left on the soil to satisfy government is minimum requirement for conservation (R, in dwt/acre) and the gross stover yield (Y_g, in dry weight tons/acre). The cost estimate below defines the determinants of stover costs (C, in \$/dwt):

$$C = \frac{15.93}{Y_g - R} + F_i$$

The first term shows all of the costs that are constant on a per acre basis. Specifically, chop and bale costs are related to trips across the field. So chop and bale costs on an output basis are inversely related to yield. The second term (Fi) contains all costs that are constant on a per unit output (ton) basis. On farm hauling costs (\$1.18/ton) are constant on an output basis because activity varies with the number of bales hauled. Fertilizer replacement costs, given above, are also proportional to residue yield. The second term is the sum of on-farm hauling and fertilizer costs. It varies from commodity-to-commodity depending on the fertilizer value.

The gross yield estimates are calculated from county average yields using biological relationships. For instance, corn stover comprises 55% of the dry matter of the corn plant (Aldrich et al. 1978; Park 1996).[4] Residue-yield relationships for other Midwestern crops are taken from Plaster (1992); Khush (1993) gives estimates of the rice straw: grain yield relationship; and Paturau (1982) provides bagasse yields from sugarcane.

An opportunity for using residue as a livestock feed may also exist in areas where there are livestock enterprises and residue supplies are exhausted in the local supply area. But quality discounts from the hay price are typical, and the extent of discounting depends on the type of residue, due mainly to variation in the protein content of the residue. The hay price discount formulas of Stohbehn and Ayres (1976) were used for residue feed value estimates. Also, a recent feed composition table gives the components present in various types of residues (Bath et al.). The 1997 values of using residue as livestock feed are \$41.90/ton for corn, \$42.51/ton for sorghum, \$21.21/ton for wheat, \$32.09/ton for barley, \$34.25/ton for oats, \$6.31/ton for sugarcane, and \$25.10/ton for rice.

The major U.S. rice production region, the Mississippi Delta, is on a major flyway for waterfowl. Further, fermenting rice straw provides food for migrating waterfowl (Young). So farmers must choose between leasing the land for hunting, or residue harvest. There is a substantial opportunity value associated with forgone hunting rights. Wailes (1999) reports the hunting value at \$20/acre, which converts to \$7.6/ton with a total residue harvest.

In the southeast, sugarcane bagasse has an opportunity value because it is burned for energy in sugar refineries. Suppose the opportunity value of heat from natural gas indicates the market supply price. The break-even price for burning bagasse or natural gas with the same profit is

$$P_b = P_n Q_n / Q_b,$$

where P is price, Q is quantity, n is natural gas, and b is bagasse. For the 1997 baseline, the breakeven bagasse price is \$34.65/ton. Supplies will be available outside the refinery if the bid exceeds this breakeven price. The bagasse supply price is in the same range as livestock feed values for other crops. The break-even price is estimated from:

$$P_n = \frac{\$2.02}{10^3 ft^3}, \textit{conversion} : \frac{44.4310^3 ft^3 \ n}{1 m.ton}, Q_n/Q_b = \frac{1 m.ton \ n}{2.59 m.ton \ b}$$

The breakeven point is calculated using yield data from Patarau (1982).

2.3. SUPPLY AND UTILIZATION TABLES FOR RESIDUES

The industrial supply of residue available at harvest cost is estimated by residue production less forage demand. The residue used for forage is also available to industrial processors above the forage value. The residue production calculation is straightforward multiplication of area and yield.

Forage demand estimates at the local county level take into account cattle population, the daily forage requirements of various types of cattle and the local availability of forage supplied by pasture. The daily forage requirements of various types of cattle are taken from the Committee on Beef Cattle Nutrition (1996) and Jurgens (1993). The length of the grazing season is estimated at the state level. The estimated growing season is defined when rapid growth degree day accumulations begin and end. The annual cattle forage demand is the annualized daily feed requirement, but the proportion of the year that cows pasture is excluded.[5] Next, local hay and silage production is subtracted from the annual forage demand. The forage requirement that is still not taken into account approximates residue demand by cattle.

The farm-level supply curve is shown for a simplified farm or county is shown as a step function in Figure 1. Initially, the harvesting cost of residue reflects the low opportunity value of unused residues. Residues may be desirable raw materials because it is not necessary to recover land costs, which have already been covered in the crop enterprise. But residue is sometimes not used for processing because it has a higher opportunity value, such as feed for livestock as forage, which defines a second step of the supply function; all residue supplies would be diverted to industrial uses at the point where energy processors meet the price of cattle owners. Finally, residue supply is vertical when all harvested residue is used by industry.

2.4. ENVIRONMENTAL CONSTRAINTS

Residue supply estimates build on the assumption of reasonable soil conservation policy and practice. Specifically, soil erosion-residue harvest tradeoffs for some representative soil and climate conditions are evaluated. Residue harvest on land in a particular soil erosion class is included in supply calculations only if erosion is below the tolerance level. Using this soil conservation criteria, a suitable tillage system is discovered by introducing more conservation-oriented systems until the

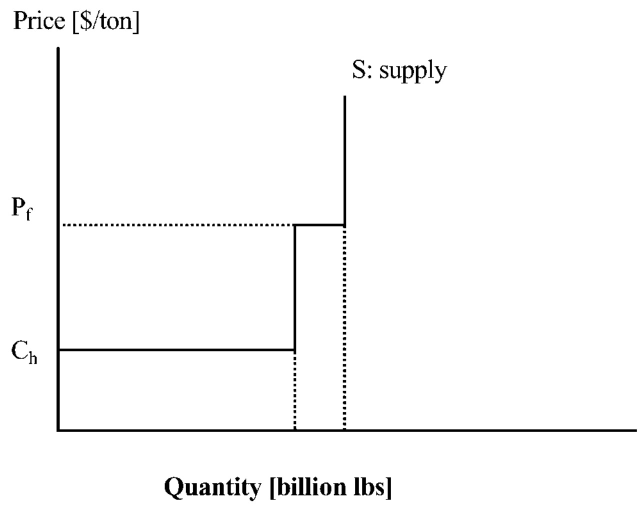

Figure 1. Crop residue supply for industrial processing.

tolerance criteria is met or the allowable residue harvest falls too low to justify harvesting expense. In any event, the soil cover is never less than the government conservation requirement, even if erosion falls below the tolerance level of erosion. Hence, environmental factors account for three types of residue supply restrictions: reducing yield in line with government conservation requirements, conservation tillage, or eliminating land from residue harvest.

Long-term aspects of soil quality maintenance also deserve attention. For instance, concerns about carbon sequestration are sometimes mentioned in connection with residue harvest. Based on research that compared corn grain to corn silage production over a 35 year period, the soil carbon does not seem to depend on the presence of residues, rather it is closely related to the choice of tillage system (Reicosky et al.; Gale and Cambardella). In this paper, the USDA conservation guidelines, which are equivalent to leaving the residues from a 35bushel/acre corn crop, are followed in all harvest calculations. Hence, a judicious combination of residue harvest and reduced tillage may jointly maintain soil carbon and increase producer profits.

Even though the rice residue area in the Mississippi Delta is on a major flyway for waterfowl, residue harvest up to the point where the ducks' food needs are met does not present a conflict. Ideally, estimation of waterfowl demands would depend on the duck population that travels through the delta, how long they stay in the Delta region, and how much is eaten in a day. Until these estimates become available, a partial residue harvest may be best.

2.5. TRANSPORT AND INPUT COSTS FOR PROCESSING PLANTS

A first approximation for plant delivery costs indicates whether transportation is an insurmountable barrier to residue processing. A concern may be that the farm cost is low in an area, but a low geographic density might still preclude residue collection for biomass processing (California Energy Commission, p. III-11). Accordingly, the transport costs are calculated for three plausible scales of biomass processing: a small scale biomass electricity plant in Denmark, a moderately sized biomass ethanol plant, and the largest scale biomass-ethanol plant. The ethanol plant sizes have been examined in engineering studies (U.S. Dept of Energy 1993). Reported estimates for residue processing feature a size that is physically possible for a region and increases the farm cost by a reasonable amount, say twenty percent at the entry point.

The organization is not known for this residue market that does not yet exist. So transport cost calculations exclude overlapping supply areas and hence the well-known inefficiencies of markets in space (Hotelling 1929, p. 52; Bressler and King 1970, p. 153). An efficient organization and a plausible scale of processing is a good place to start. Otherwise, estimates of resource and technology benefits might become entangled with deadweight losses associated with inefficient market organizations.

2.6. SINGLE PRODUCT

Methodology for farm cost and delivered plant cost are now given for the one product case. The main factors that influence the spread between farm cost and delivered plant cost are the density of residue, the capacity of processing plants and local truck-hauling rates.

The transportation component of residue costs increases with factory capacity because greater distances are traveled to secure supplies. The physical relationship between distance from the plant (r) and available supplies (Q) from one crop can be approximated by $Q = (\Pi r^2)dy$, which is the product of the area of a circle of radius r, πr^2, and the density of residue, dy. In turn, residue density is the product of residue yield (y) and the density of planted crops in the total area (d). For example, d = 320 acres of residues/mi^2 in a county with one-half of the land in corn and maybe y = 3 ton residues/acre, giving a volume density of dy = 963 ton/mi^2.

When $\tilde{Q}$ is set at the capacity of the processing plant, the maximum distance required (r^*) by the plant can be obtained by rearranging $r^* = \sqrt{\tilde{Q}/(\Pi dy)}$.

For the cost-distance relationship, notice that the production obtained from a ring of a given distance from the plant is given by the product of the circumference of the circle, the width of the ring, and the density of residue $\triangle Q = (2\pi r)(dy)\triangle r$. Then the marginal cost of expanding the outer circle by the increment $\triangle r$ is given by $C'(r) = P(r)(2\pi r)(dy)\triangle r$. P(r) is the price gradient function describing the price-distance surface – the price gradient is the sum of residue harvest and transport costs. With a linear price gradient, the total cost function $C(r) = \int_0^{r*} P(r)(2\Pi r)(dy)dr$ becomes $C(r) = (dy)(2\pi)\int_0^{r*}(P_0 + tr)rdr = (\pi r^{*2})(dy)\left[P_0 + \frac{2t}{3}r^*\right]$ where t is the freight rate in \$/ton/mile. So the average input cost (AIC) is $C(r^*)/Q(r^*) = P_0+(2/3)(tr^*)$.

Hence, the spread between AIC and farm costs, $2tr^*/3$, increases with the truck rate and the maximum distance. In turn, the supply radius increases with plant capacity and declines with supply densities.

2.7. MULTIPLE SUPPLIES AND INPUT COSTS

When there are several different types of crop residues in an area, the farm supply function for crop residues would likely have several steps that correspond to the residue supplies of a particular crop. Residue costs vary from crop-to-crop because the yield and the opportunity values for fertilizer replacement are different. This section considers the determination of efficient supply areas when there are several types of crop residues.

Suppose P_{0i} is the harvest cost for crop residue i. Also, r_i is the radius of the supply area for crop i. Also assume that crop 1 has lowest harvest costs, crop 2 is second-lowest, and so on. A processor seeking the minimum cost input will expand the supply area so the cost of marginal supply is equal for each type of residue. So the conditions

$$P_{01} + r_1 t = P_{02} + r_2 t \quad (1)$$
$$P_{01} + r_1 t = P_{03} + r_3 t$$

identify the boundaries of supply area 2 and supply area 3 (r_2 and r_3) when the boundary of 1 (r_1) is given in the three product case.

To determine the market areas for each type of residue, notice that capacity output must equal the sum of production from all residue types

$$\tilde{Q} = \sum_i \Pi\, r_i^2\, d_i\, y_i \quad (2)$$

when there are three supply areas with radii r_1 , r_2 , and r_3 , equations (1) and (2) above provide a set of three equations that can be solved for the radii of the market areas. The equations in (1) can be substituted into (2) to eliminate r_2 and r_3. Then the quadratic formula can be used to solve for the radius r_1 that has efficient boundaries and fills the plant capacity.

The case when higher cost residues are not used can be identified without recourse to formal mathematical programming. For instance, the market border condition,

$$P_{01} + r_1 t = P_{02} + r_2 t,$$

also identifies the utilization threshold for the second (or third) crop. Specifically,

$$P_{01} + r_1 t = P_{02} \text{ when } r_2 = 0.$$

In words, the farm cost of type 2 residue adjacent to the plant equals the cost of type 1 residues that are delivered from r_1 miles out at the threshold for type 2 residue. Generally, the supply radius for crop i when crop j is on the entry threshold (Rij) is

$$\begin{aligned} R_{12} &= (P_{02} - P_{01})/t \\ R_{13} &= (P_{03} - P_{01})/t \\ R_{23} &= (P_{03} - P_{02})/t. \end{aligned}$$

Next, we can check if the plant's capacity has been filled by the time an entry threshold is reached. First, calculate the outputs associated with the 2 product and 3 Product boundaries

$$\begin{aligned} \overline{Q}_2 &= \Pi\, R_{12}^2\, d_1\, y_1 \\ \overline{Q}_3 &= \Pi\, R_{13}^2\, d_1\, y_1 \;+\; \Pi\, R_{23}^2\, d_2\, y_2 \end{aligned}$$

All three possible cases can be defined with entry points and associated outputs. First, a plant's capacity is filled with one crop before the second crop is used if $\overline{Q}_2 > Q$. Further, a two product supply fills capacity if $\overline{Q}_2 < Q < \overline{Q}_3$. Finally, a three product supply area is used if $\overline{Q}_3 < Q$.

Equipped with a list of included crops and supply areas (r_1, r_2, r_3), the plant's residue costs can be defined. Specifically, the total costs of residue type i are

$$C(r_i) = (\Pi\, r_i^2)(d_i\, y_i)\left[P_{0i} + \frac{2}{3} t r_i\right]$$

with linear transport costs. Also, the output produced using residues of type i are

$$Q_i = \Pi r_i^2\, d_i\, y_i$$

Finally, the average input costs are defined by

$$AIC = \left(\sum_i C(r_i)\right)\left[\sum_i Q_i\right].$$

So average input costs depend on the average harvest costs and transport charges,

$$AIC = \overline{P_0} + 2/3t\bar{r} \;\; \textit{where} \;\; \overline{P}_0 = \sum_i S_i\, \overline{P}_{0i},\; \bar{r} = \sum_i S_i\, r_i,\; S_i = Q_i / \sum Q_i$$

when several crops provide residue supplies – S_i refers to the share of supply provided by residue i.

3. Crops and Cultivation Methods Per Region

The regions selected for this study are areas with high density production of a major crop that share common agronomic practices. County-level definitions of regions are used because only parts of most states should be included. County data also

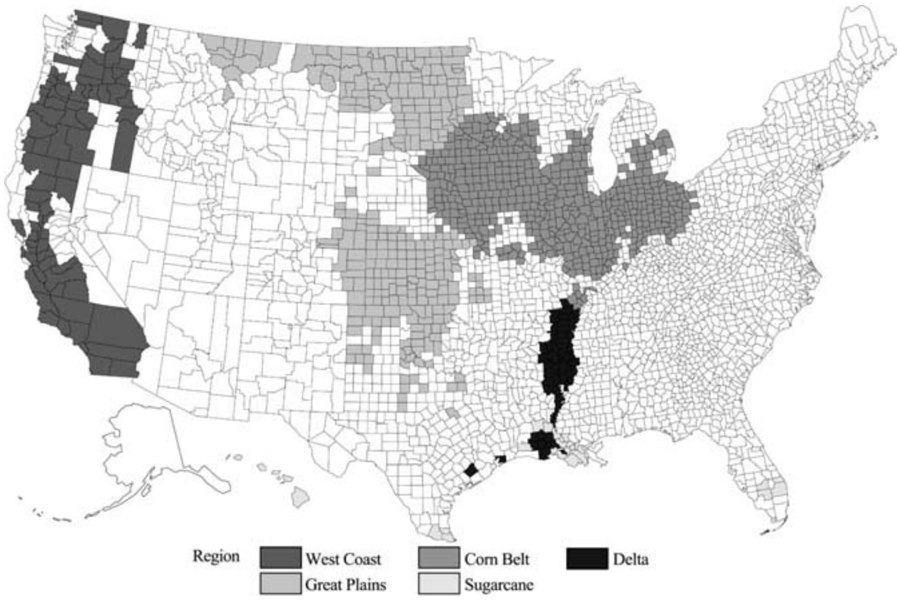

Figure 2. Crop residue regions.

helps to uncover the extent of variation in production costs. The four agricultural regions, the Corn Belt, Great Plains, West Coast, and South are shown in Figure 2.

Distinct crops and cultivation methods are found in each region. Only corn residue (stover) has sufficient volume for harvest in the Corn Belt. Wheat is the main crop in the Great Plains, but residue (straw) production and erosion potential varies with the prevailing agronomic practice. The prevailing practices are continuous winter wheat in the south and east, a two year plant-and-fallow cycle of winter wheat in the arid west, and spring wheat in the Northern Plains. The crop substitution possibilities also vary around the Great Plains. The main substitute crops, barley and oats in the north, dryland corn and sorghum in the continuous wheat area, and sorghum or irrigated corn in the wheat-fallow region, all have sufficient residue for harvest. The crop choices and agronomic practices on the West Coast are similar to those in the Great Plains. Rice and Sugar are the main southern crops with residue potential. Most rice production occurs in the Mississippi Delta. Cane sugar is grown in the southeastern United States (Louisiana and Florida). Bagasse is the portion of the sugarcane stalk that remains after the sugar is extracted in the refinery.

4. Erosion Management

Some residue should be left as a soil cover on land where residue is harvested. The Soil Conservation Service (SCS) of the U.S. Department of Agriculture already requires that 30% of the *surface area* of the field be covered in the spring (Soil Conservation Service 1991). For corn, 1430 lb/acre of chopped corn stover left in the fall fulfills that requirement. For wheat and other small grains 715 lb/acre of fall residues satisfy the requirement including the loss of residues during the winter (Wischmeier and Smith 1978). For winter wheat-fallow, it is assumed that the winter loss occurs twice, so the minimum fall residue would be 1020 lb/acre. Net residue yield estimates below leave at least the recommended amount of fall residue for a soil cover. Further, residues should be harvested only from land where soil can be conserved. There is a tradeoff between residue remaining after harvest and erosion. But soil type and other land characteristics (e.g., slope of the land) influence the position of the tradeoff line. Tradeoff calculations use representative soil and climate conditions. Land is included in residue harvest when the erosion level with the government conservation requirement stays below tolerance level. The tolerance level is defined for each soil type. The tolerance approximates the annual regeneration of soil through root decomposition, etc.; typically the tolerance level is between 3 to 5 tons/acre.

Soil erosion estimates for representative soils from several land classes and alternative residue-cover schedules were calculated. Land quality was taken into account using the (SCS) land classification (Soil Survey Staff). The classification includes a ranking for erosion potential (Klingbiel and Montgomery 1961). Class I soils have no erosion or other use-limiting features. Class IIe soils have moderate potential for erosion. Higher classes, IIIe to VIIIe , have increasing slope, less durable soil structures and increasing soil erosion potential. Water erosion calculations used the universal soil loss equation (Renard et al. 1993; Hawkins et al. 1995). For wind erosion in the Great Plains, procedures given by Skidmore and Woodruff were employed. Additionally, several tables from Soil Conservation Service Manuals were used for erosion estimates at a given location (Soil Conservation Service, Kansas 1982).

Finally, reduced tillage methods may be required for soil conservation. For corn, a 9.5% reduction of corn yields was imposed assuming everyone switches to Mulch till, a reduced tillage method, in the corn belt. In lower moisture environments like eastern Kansas, however, the evidence suggests that there is not a yield reduction, so the 9.5% reduction will lead to conservative stover yield estimates. For wheat and other small grains, no-till farming was assumed throughout this reported tradeoff analysis but a yield discount was not applied.

4.1. CORN BELT

Figure 3 illustrates corn crop residue-erosion tradeoff thresholds for three different land classes. The representative soils were used in a study of corn production in Iowa (Park 1996, p. 74). The "M" on the axis indicates the government conservation recommendation. Virtually any residue harvest on the Class I soil gives soil erosion that is less than tolerance (5 ton/acre). Similarly, erosion remains below tolerance on the class II soil provided that the government's guideline is met. A 50% stover harvest would be marginally within the tolerance on the Class IIIe

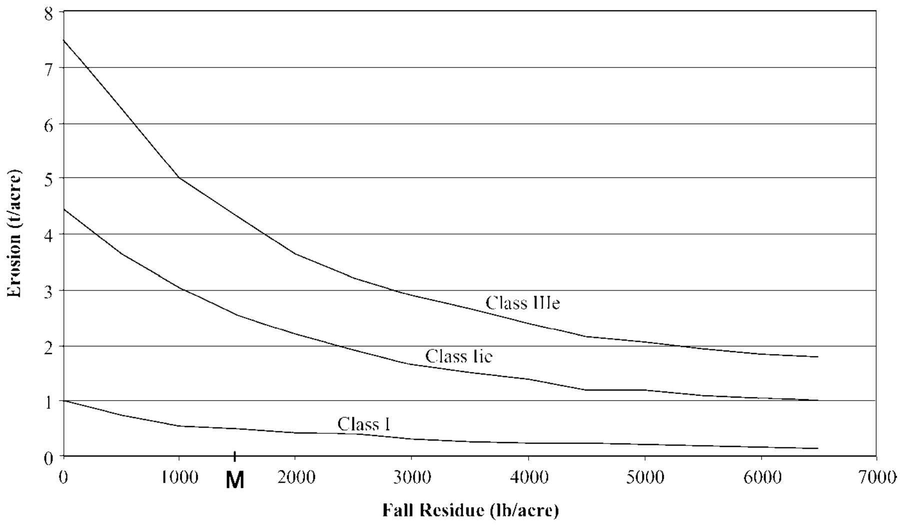

Figure 3. Corn stover-erosion tradeoff for corn in the corn belt (water erosion).

soil. So subsequent calculations exclude land from classes III and higher from the residue harvest.

4.2. GREAT PLAINS

The wind and water erosion estimates used Hayes's (1975) estimates of wind and water erosion for a representative wheat-fallow mulch-till system in western Nebraska as a reference point. After replication of the base case, erosion estimates were adjusted for other wheat-fallow locations.[6] Also, a no-till system is assumed. Estimates for eastern Kansas and northwestern Minnesota exclude the fallow year. Erosion-residue tradeoffs were calculated in representative cases for each major crop and cultivation method. Three typical soil types and locations were used: eastern Kansas for continuous winter wheat, western Kansas for the winter wheat-fallow area, northwest Minnesota for Spring wheat.

The criterion for including land in the residue harvest is that the sum of wind and water erosion rates are within tolerance after a residue harvest. The charts in Figure 4 depict the harvest margins. Generally, a substantial residue harvest is consistent with erosion rates moderately below tolerance. For continuous winter wheat on class II land (Figure 4a), the total erosion rate is about 3 ton/acre with a 715 lb/acre residue cover, which is below the 5 ton/acre tolerance. For spring wheat on class IIIe land (Figure 4b), the total erosion rate is about 6 ton/acre with a 750 lb residue cover, which is near the tolerance. For winter wheat/ fallow on class II land, the erosion rate drops to the 5.0 ton/acre tolerance when a fall residue of about 1500 lb/acre is left after harvest (Figure 4c).

Thus, harvest of wheat residues up to the 715 lb/acre government recommendation (required to comply with soil cover regulations) is suitable for continuous winter wheat in land classes I or II. Similarly, a removal of residue for spring wheat that leaves only the government's minimum cover appears sensible for land in classes I, II or III. A partial harvest, which would leave at least 1500 lb/acre residue cover, is indicated for the wheat-fallow tradeoff on class II land in western Kansas. In the last case, the 30% loss is a critical assumption for the marginal results. Slightly lower residue losses move the class II wheat-fallow case into a higher harvest margin.

Erosion estimates for sorghum and corn on the class I land in eastern Kansas (Figures 4d and 4e) show sorghum harvest at the 5t/a tolerance with the 1430 lb/acre cover. Also, the corn estimate falls above tolerance, unless 2500 lb/acre of residue remains. Wind erosion is the limiting factor in both of these cases. Thus, residue harvest on class I land planted to corn or sorghum is suitable; but the unharvested corn residue should exceed the minimum government allowance.

4.3. DELTA

Water erosion is not a problem on the flat land of the Mississippi Delta thus the standard SCS recommendation for soil cover is not relevant to the flat soils in the Mississippi River Basin.

4.4. SOUTHEAST

Sugarcane bagasse is part of the raw sugarcane stalk. So harvest and transport of bagasse to the refinery already occurs as part of the harvesting process. Thus, using bagasse has no change on soil conditions because it is already being removed.

5. Cost Estimates

A summary of cost estimates is given in Table I. These Harvest Cost estimates refer to the major crops at locations of the representative soil types. Hence cost estimates refer to important production regions and typical circumstances. Transport costs that are compatible with the geographic density of residues at a particular location are also given. Estimates are based on the harvest and transport functions given earlier. Variation in harvest cost stems from variation in yield, conservation allowances and opportunity values. The commodities ranked from lowest to highest are: corn, wheat and sorghum in the continuous winter wheat area, spring wheat, and winter wheat in the plant-fallow area. Details of the harvest cost calculations are available upon request.

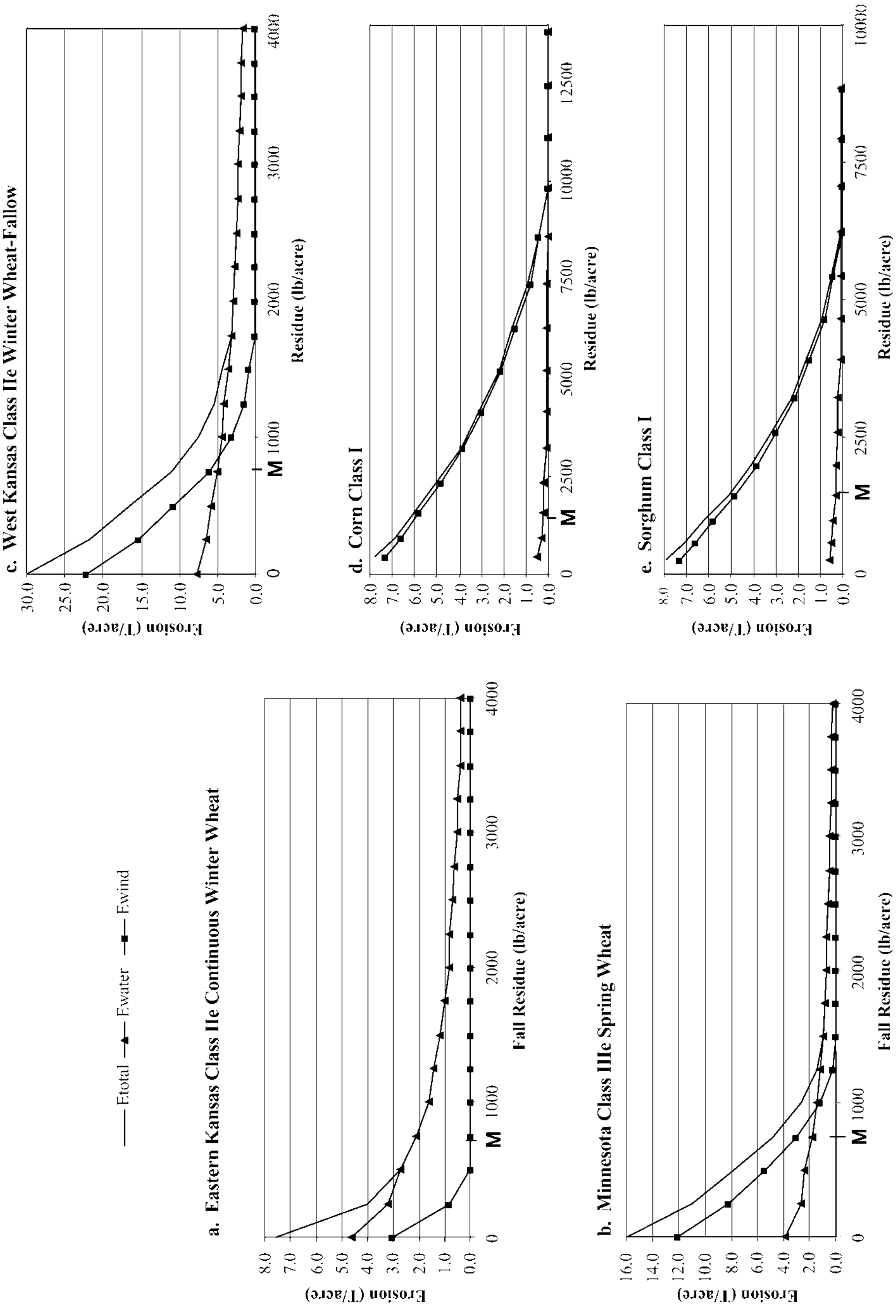

Figure 4. Crop residue-erosion tradeoff for the Great Plains (wind and water erosion).

Transport costs depend on the density of crop residues, the size of the processing plant, and a given hauling rate. Transport cost estimates use plausible biomass plant capacities and typical density conditions. For Story County, IA, density is dy = 889.4 tons per square mile, which is enough to support a very large ethanol plant ($\tilde{Q}$ = 2.9 million tons of residue) with moderate transport costs of about $2.15/ton. But the transport cost differential between the large plant and the small plant increases rapidly when the supply density falls below $d \cdot y$ = 500 tons per square mile. Moderate transport costs are given in Table I with a mid-sized ethanol plant in the spring wheat and rice areas, where residue density is in the middle of the range. The lowest density in Table I, Riley County, Kansas, gives moderate transport costs with an electric plant that is much smaller than the mid-sized ethanol plant. Ultimately, a full analysis of economies of scale should be conducted. Nonetheless, these estimates show the feasibility of biomass processing with some plausible plant scales. Crop residues would be available to processing plants in the $14/ton to $30/ton range for all major field crops and regions.

Sugarcane bagasse is an exception to the harvest cost function. The harvest, transport and fertilizer replacement costs for bagasse are associated with the primary sugar crop. Hence, the costs of harvesting and delivering bagasse to the plant are essentially zero.

6. Supply Function Estimates

The supply curves in Figure 5 were developed using a two-step procedure. First, the county data was sorted by cost while retaining the associated net residue supply volume for each county. Second, quantities were cumulated for the total amount that would be available in local residue markets at a given price. So variation in yields around a region will be an important reason for supply variation. Further, combined farm and transport costs are used to access the feasibility of biomass processing.[7]

The Corn-Belt supply curve for corn stover (Figure 5a) suggests a highly elastic response at the plant level. In a $6/ton range from about $15/ton to $21.00/ton, the supply from the Midwest would go from zero to about 90% of the available stover supply (180 bil lbs). The related farm level costs vary in a narrow $2/ton range from $12/ton to $15/ton up to the point when 90% of stover is used by processors. Notice that Figure 5a has been sorted by delivered cost, so the associated farm cost may be lower for a sub-region that has a higher delivered cost when the residue density is lower and transport costs are higher. Figure 5a includes transport costs for a large ethanol plant. The difference between the cost curves for large plant starts about $3/ton but then widens rapidly above 175 million lbs because locations with high-density corn supplies are exhausted. Finally, a 10% increase in the stover volume (not shown) is available at a much higher price of $42/ton when these residues are bid away from livestock.

Table I. A summary of residue harvest and transport costs

Commodity	Location	Harvest Cost ($/ton)	Residue Density (t/mi^2)	Transport Cost ($/t) *[type of plant]*	Total Cost ($/ton)
Corn	Story County, IA	12.73	889.4	2.15 *[large ethanol]*	14.88
Winter Wheat, continuous	Riley County, KS	15.66	28.47		17.52
Sorghum		16.6	12.36		18.46
		sum	40.83	1.86 *[electric]*	
Winter Wheat, continuous	Ford County, KS	20.97	26.38		24.36
Winter Wheat, fallow		29.78	45.28		33.17
Sorghum		16.73	0		20.12
Corn		12.43	0		15.82
		sum	71.66	3.39 *[ethanol]*	
Spring Wheat, continuous	Norman County, MN	19.42	246.3		21.00
Barley		17.34	77.8		18.92
Oats		18.56	3.96		20.14
		sum	328.06	1.58 *[ethanol]*	
Rice	Arkansas County, AR	20.32	283.24	1.70 *[ethanol]*	21.90
		Transport cost ($/ton/mile)			0.1
		Plant input requirements (tons)			
			100000	electric plant	
			581000	ethanol plant	
			2900000	large ethanol plant	

The residue supply estimate for the Great Plains includes several residue sources that are available at different costs. The prices in the residue supply curve of Figure 5b are the average input costs for a plant that follows the least cost rule for use of inputs and the corresponding quantities come from the efficient market areas. Other supplies are available at the higher cost after efficient market areas fill up the region. The Great Plains supply curve (Figure 5b) includes the transport charges associated with a middle-sized ethanol plant. The crop residues would become available at the plant over a $21/ton range from $14/ton to $35/ton, at which about 90% of the residue supplies become available to the market. The spread between the farm and plant cost is irregular, due to the many combinations of farm costs and residue densities. Typically, the spread varies in a narrow range around until about one half of the residues are supplied. For the last one-half of residue supplies, delivered costs escalate rapidly, and farm costs fluctuate widely from county-to-county; the average spread between delivered and farm cost at 75 billion lbs is about $10/ton, and widening to$20/ton for counties with low farm costs but sparse supplies. The increasing input costs reflect declining residue yields, increasing conservation requirements, the entry of wheat feed residues, and declining density of available residues.

The West Coast supply curve, shown in Figure 5c, includes the transport charges for an electric-biomass plant. The initial concave shape of the upper supply schedule indicates that there is a pocket of concentrated low-cost residue. Otherwise, there is a wide range of supply prices. The rightward shift at $42/ton reflects the diversion of residues from animal feed to industrial supply. The typical spread between the farm and plant cost widens from about $2/ton to $15/ton from initial supplies to the point where livestock feed are diverted. In some areas with sparse supplies and low cost farm supplies, though, the spread can widen $30/ton in some counties with small amounts of high yield residues.

The Delta supply curve in Figure 5d reflects delivered costs for a moderately-sized ethanol plant. This schedule is flat in the $20–25/ton range, because yields are uniform and densities are high in much of the region. The vertical position would be comparable to the corn supply curve, except for the substantial opportunity value of hunting leases when residues are not harvested. The associated farm cost schedule is even flatter, in the $20/ton–$23/ton range, suggesting that declining densities are a factor in increasing delivered plant costs.

The bagasse in cane provides slightly more energy than the modern plant requires: 100 tons of sugarcane produces 25 ton bagasse (49% moisture mill run). and 9 tons are not needed for sugar processing (Patarau 1982). Some modern facilities also install generating equipment and sell the surplus as electricity. But one author's informal survey suggested that Louisiana refiners do not sell surplus electricity. Hence, 36% of bagasse supplies would be available at the refinery at almost no cost. However, the remaining 64% has an opportunity value in sugar refining, and would be available to bio-fuel processors only if they beat the value from burning the bagass.

7. Biomass Supply and Capacity

The national energy supply potential of crop residues for the United States is summarized in Table II. Table II summarizes and aggregrates regional supplies of crop residues. In all cases, net production includes conservation adjustments to yield and erosion-based restrictions on harvested area. Feed use indicates livestock demand net of hay supplies. Industry supply refers to unused residues that would be available to a biomass processing industry. The total biomass supply ranges from 297 to 313 bil lbs, depending on the price level. Cornbelt residues account for

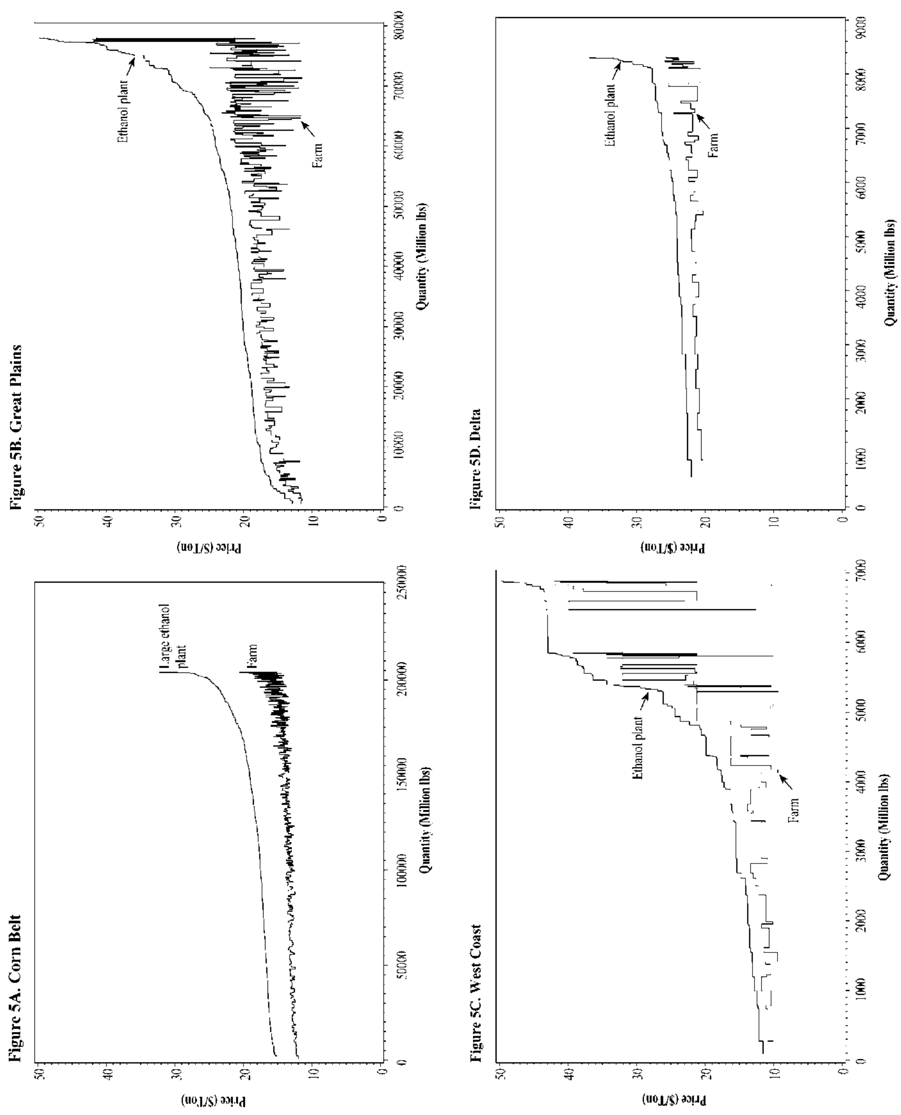

Figure 5. Crop residue supply curves.

Table II. biomass from crop residues: supply and capacity for 1997 baseline

Region	Net Residue Production	Feed Use	Industry Supply
	mil lbs.		
Corn Belt	207,199	23,786	197,844
Great Plains	81,040	9,994	71,042
West Coast	7,377	2,573	4,805
Delta (Rice)	10,435	1,168	9,246
Southeast (Sugar Bagasse)	7,114	0	7,114
Total	313,165	37,521	290,051

2/3 of available residues. But the Great Plains account for nearly 1/4 of available supplies. The other regions provide pockets of low-cost crop residues. The average cost at processing plants ranges from $15/ton in the corn belt to $42/ton when competition for residue feed occurs on the west coast.

There is also potential for growth in the crop residue resource due to crop yield growth and declining livestock demand for forage if the trends of the last two decades continue. First, a repeat of crop productivity growth of 56% over the last two decades would account for another 170 billion lbs of crop residues. Also, the 10% trend-level decline in cattle populations of the last two decades could account for another 75 billion lbs of available biomass in another two decades. Hence, the biomass residue supply could grow to about 500 bil lbs during the next two decades.

Even existing residue supplies could make a difference in U.S. energy markets. Tomorrow's biomass ethanol technology could displace petroleum inputs (Gallagher and Johnson). The petroleum displacement with all crop residue supplies is 0.376 bil bbl oil.[8] Hence, ethanol processing from residues could displace 12.5% of U.S. petroleum imports in the 1997 baseline year. Where moderate processing scales are indicated, electricity displacement could occur with today's biomass conversion technology. Using the crop residue-electricity yields from Larsen (1997), the electricity equivalent of the residue capacity is 172.4 bil. Kw-hr.[9] Hence, biomass electricity from residues could physically account for 5% of electricity consumption. However, energy displacements only refer to possibilities at present. The biomass ethanol technology is still under development. Biomass electricity processing is in operation in Denmark but its competitiveness in the United States is unknown.

8. Summary and Conclusions

This study has examined biomass supply from crop residues, taking into account cost and environmental factors. First, the analysis suggests that reduced tillage and partial residue harvest may maintain soil quality and increase producer profits. Corn Belt, Great Plains, and West Coast participation is possible with judicious selection of crops and areas. Second, residues are probably the lowest cost form of biomass supply. Throughout the cornbelt, residue costs have a narrow range, from \$16–\$18/ton, even after making allowances for delivery to a large plant. The range of costs is wider in the Great Plains owing to the diversity of growing conditions, conservation requirements, and forage demands. The eastern section of the Spring wheat area has extensive residue supplies at moderate cost. Also the eastern section of the Winter wheat belt has a cost advantage when the combination of feed grain residues, wheat straw and residues diverted from feed are combined. The remaining regions, the West Coast, the Delta, and the Southeast, have pockets with residue supplies. Overall, the cost estimates for residues compare favorably to biomass crops in the cornbelt, which are typically in the \$40/ton range (Parks 1996).

Crop residues are a low-cost resource with the potential to displace 12.5% of petroleum imports or 5% of electricity consumption in today's markets. The residue resource also has growth potential from crop productivity and declining livestock demands for forage. Taken with other potential sources, like cropland that has been idled under government programs and hay land, biomass supply from crop agriculture could account for a substantial share of our energy consumption.

The residue supply estimates of this paper refer to the supply potential and social cost for an industry that does not yet exist. Several barriers must be overcome before this potential can be realized. First, a successful investment in processing research must occur. Biomass ethanol, for example, appears on the horizon, but has not been adopted on a sufficient scale to confirm industrial success. Second, the transportation, handling and marketing system must evolve to an efficient form. Existing handling systems have been designed for livestock feed and the transport technology has been designed for other commodities. High bids for residue use today reflect residue feed values, the need to accumulate harvesting and transportation capital, or high profit margins in a thin market. Third, the risks associated with residue processing should be quantified; the estimates of this paper used trend values of residue yields and typical estimates of pasture season length and forage demands. Year-to-year variation in weather supplies could have a bearing on the optimal processing scale or feasibility of residue processing at some locations. However, the ability to cope with feedstock variability will likely be part of the landscape after society makes the transition to renewable fuels and energy. In any event, preliminary indications suggest that the U.S. agriculture sector will benefit from increased presence in energy and industrial product markets, given steady productivity growth and stagnant traditional markets.

Notes

1. Who incurs costs and reaps profits depends on how market organization evolves. All farm, transport and processing costs would be born by members of a coop, a common organization in the U.S. ethanol industry.
2. U.S. customary units are used because it is standard in the U.S. agriculture industry. Some useful conversion factors are: 1 hectare = 2.471 acres, 1 metric ton = 2205.07 lb., and 56 lbs. = 1 bushel, where "lb" abbreviates pounds. Also, prices are given in dollars per short ton and 1 short ton = 2000 lb.
3. The labor requirements for the chopper and the bailer are the same. The calculation is:
$$\frac{1 \text{ mach hr}}{4.65 \text{ acre}} \times \frac{1.1 \text{ man hr}}{1.0 \text{ mach hr}} \times \frac{\$7.76}{\text{man hr}} = \frac{\$1.83}{\text{acre}}$$
4. Lipinski et al. (1977) use a slightly lower estimate for the stover component of the corn plant's dry matter (p. 106). But recent experiments in Iowa Park (1996) confirm calculations by Aldrich (1978).
5. Daily forage requirements are 27.6 lb/day for beef cows, 25.2 lb/day for milk cows, 13.2 lb/day for beef heifers, 9.6 lb/day for milk heifers, 30.0 lb/day for bulls, and 5.8 lb/day for steers. The grazing season length varies from 137 days for North Dakota to 257 days for Louisiana. The details of pasture season length estimation and feed requirements by type of cow are available from the authors upon request.
6. The climate factor, "C," measures the erosive potential of wind and soil moisture, expressed as a percent of the C-factor for Garden City, Kansas. The soil index, "I," measures erosion from a given soil in a field with reference wind exposure and tillage conditions when the climate factor takes a reference value (Soil Conservation Service, Iowa).
7. The assumed market areas are circles without overlap. So a small fraction of a region's residues may remain after all supply areas are filled, and the marginal cost for the last fifteen percent of a region's supply may be underestimated. Also, market areas sometimes extend beyond one county. But the density estimate is likely accurate within the usual range, where the county's radius is exceeded by less than fifty percent.
8. The calculations are:
$$320 \text{ billion lb res} \times \frac{1 \text{ gal ethanol}}{0.0083 \text{ ton res}} \times \frac{1 \text{ ton res}}{2000 \text{ lb res}} \times \frac{1 \text{ bbl}}{42 \text{ gal}} \times \frac{0.84 \text{ bbl oil}}{\text{bbl}}$$
$$= 0.376 \text{ billion bbl oil.}$$
9. The calculations are:
$$313 \text{ billion lb res} \times \frac{1 \text{ Kw-hr}}{0.000998 \text{ mt res}} \times \frac{1.1 \text{ mt ton res}}{\text{ton res}} \times \frac{1 \text{ ton res}}{2000 \text{ lb res}}$$
$$= 172.4 \text{ billion Kw-hr.}$$

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Appendix*,**

Variable	Description	Units
C	Residue harvest costs, direct cash outlays	\$/dwt*
Y_g	Gross residue yield	dwt/acre
R	Government residue cover requirement	dwt/acre
F_i	Farm hauling and fertilizer costs, direct cash outlays	\$/dwt
P_i	Price of commodity i	\$/dwt
Q_i	Quantity of commodity i; i = n for natural gas, b for bagasse	dwt
r	Distance to the processing plant from a farm	miles
Q	Quantity available to the processing plant	dwt
d	Area density of the residue source	acres/ square miles
y	Net residue yield (after government cover requisite)	dwt/acre
$\tilde{Q}$	(Input) capacity of a processing plant	dwt
r*	Maximum distance farm supplies move to supply a plant of capacity $\tilde{Q}$	miles
P(r)	Sum of unit residue harvest and transport costs at a given distance from the plant	\$/dwt
C(r)	Total cost at the plant for residues obtained between 0 and r miles from the plant	\$
$C'(r)$	The derivative of C wrt r	\$/mile
P_0	Farm cost	\$/dwt
t	Freight rate	\$/dwt/mile

Variable	Description	Units
AIC	Average input cost at the plant	\$/dwt
P_{0i}	Farm cost for residue from crop i	\$/dwt
r_i	Radius of distance to plant for crop i	miles
d_i	Area density of residue from crop i	acres/ square mile
y_i	Net residue yield for crop i	dwt/acre
R_{ij}	The supply radius for crop i when crop j is on the entry threshold	
$\overline{Q}_i$	The residue supply associated with the entry threshold for crop i	
Q_i	The supply of residue from crop i	
$\overline{P}_0$	Share-weighted average farm cost of all residue types	\$/dwt
$\bar{r}$	Share-weighted average maximum distances from the plant	miles

* dwt is an abbreviation for dry weight tons.

** Variables are given in the order that they are used in the paper.