Current and Potential U.S. Corn Stover Supplies

R. L. Graham,* R. Nelson, J. Sheehan, R. D. Perlack, and L. L. Wright

ABSTRACT

Agricultural residues such as corn (*Zea mays* L.) stover are a potential feedstock for bioenergy and bio-based products that could reduce U.S. dependence on foreign oil. Collection of such residues must take into account concerns that residue removal could increase erosion, reduce crop productivity, and deplete soil carbon and nutrients. This article estimates where and how much corn stover can be collected sustainably in the USA using existing commercial equipment and estimates costs of that collection. Erosion constraints to collection were considered explicitly, and crop productivity and soil nutrient constraints were considered implicitly, by recognizing the value of residues for maintaining soil moisture and including the cost of fertilizer to replace nutrients removed. Possible soil carbon loss was not considered in the analysis. With an annual production of 196 million Mg of corn grain (~9.2 billion bushels), the USA produces 196 million Mg of stover. Under current rotation and tillage practices, ~30% of this stover could be collected for less than \$33 Mg^{-1}, taking into consideration erosion and soil moisture concerns and nutrient replacement costs. Wind erosion is a major constraint to stover collection. Analysis suggests three regions of the country (central Illinois, northern Iowa/southern Minnesota, and along the Platte River in Nebraska) produce sufficient stover to support large biorefineries with one million Mg per year feedstock demands and that if farmers converted to universal no-till production of corn, then over 100 million Mg of stover could be collected annually without causing erosion to exceed the tolerable soil loss.

Bioenergy and biobased products are essential elements of the U.S. national policy to increase energy supplies and reduce dependence on foreign oil (USDOE-USDA, 2002a, 2002b). The United States Department of Energy is actively supporting research to lead to the development of future biorefineries, which convert ligno-cellulosic biomass feedstocks to ethanol, power, and biobased chemicals (USDOE, 2003). The Biomass Research and Development Act of 2000 (Title III of the Agricultural Risk Protection Act) has fostered USDA and U.S. Department of Energy bioenergy research solicitations in recent years.

Existing agricultural residues, such as stover from corn grain production, are an obvious source of biomass especially for the near term. The collection and removal of these residues that would otherwise be left in the field must be done in a sustainable fashion and not impair the productivity of the land, diminish water quality, or result in unwanted carbon emissions. Two recent articles examine the issues of sustainable collection of corn stover (Wilhelm et al., 2004; USDA-NRCS, 2003). Both studies suggest that some collection of corn stover is sustainable but do not indicate how much or where in the USA collection might be sustainable.

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The objective of this analysis was to estimate the location and quantity of corn stover that might be sustainably collected in the United States and the cost of collecting that stover. With regard to sustainability, the analysis focused on limiting water and wind erosion. Potential effects on crop productivity were partially addressed by considering preservation of soil moisture and the replacement cost of nutrients lost with stover removal. The need to maintain soil carbon was not considered. Although soil carbon and crop productivity are important considerations, the knowledge base for quantitatively assessing the amount of stover that needs to remain on the field to maintain soil carbon or crop productivity is limited, although it is growing (see Wilhelm et al., 2004; USDA-NRCS, 2003; Linden et al., 2000). The model Century (Sheehan et al., 2004) has been applied to address soil carbon aspects of stover removal but not under all the corn production situations that occur within the USA. The USDA Soil Conditioning Index (USDA-NRCS, 2006) can be used to assess the effect of stover removal rates on soil carbon. However, in its current form with manual input, the Soil Conditioning Index is not practical to run for the thousands of corn production situations that occur in the USA.

METHODS

Using readily available data from the USDA, we sought to capture the complexities of corn production practices in the USA and their effect on corn stover supplies. Crop yields, crop rotations, soils, and tillage practices were considered at the finest spatial resolution available, generally the county. The supply of sustainably collectable stover in the USA was estimated by (i) calculating the stover produced per hectare of corn production in a county, (ii) calculating the amounts of stover required to stay in the field (Mg ha^{-1} yr^{-1}) to meet sustainability and operational constraints for the suite of typical corn rotation and tillage practices in the county, (iii) calculating the collectable quantities of stover (Mg ha^{-1} yr^{-1}) under each of those same practices, (iv) calculating the cost of collecting stover (\$ Mg^{-1}) under those same practices, and (v) estimating quantities (and their respective collection cost) of collectable stover in a county given the corn production practices of that county. These five steps are described in the following text.

Stover Production

The amount of stover produced per hectare of corn grain production was estimated using corn grain yield values and a

Abbreviations: HI, harvest index; hp, horsepower; NASS, National Agricultural Statistics Survey; NRCS, National Resource Conservation Survey; T, tolerable soil loss (Mg ha^{-1} yr^{-1}).

Table 1. Residue to grain ratios, associated residue harvest index, and factors used to convert USDA values of grain production from bushels to dry mass.†

Crop	Dry weight residue/grain ratio	Residue harvest index	Factor used to convert bushel of grain to dry mass grain
			kg bushel^{-1}
Corn	1:1	0.5	21.5
Spring wheat	1.3:1	0.57	23.6
Soybean	1.5:1	0.60	23.7
Winter wheat	1.7:1	0.63	23.6
Barley	1.5:1	0.60	18.6
Oat	2.0:1	0.67	12.5

† Factors are based on Wilcke and Wyatt (2002).

stover mass to grain mass ratio of 1:1 (i.e., a dry weight harvest index [HI] of 0.5) as reported by Gupta et al. (1979). Because corn grain production is reported by the USDA in units of bushels and acres, for conversion to units of mass it was assumed that a bushel of corn had dry grain mass of 21.5 kg (56 lb at 15.5% moisture) (Wilcke and Wyatt, 2002). Stover production was calculated with the following equation:

$$\begin{aligned}\text{Stover (Mg ha}^{-1}\text{ yr}^{-1}) = {} & \text{yield (bushels corn acre}^{-1}\text{ yr}^{-1})\\ & \times 21.5 \text{ (kg corn bushel}^{-1})\\ & \times 1.0 \text{ (kg stover kg}^{-1}\text{ corn)}\\ & \times 1000 \text{ kg Mg}^{-1}\\ & \times 0.405 \text{ ha acre}^{-1} \qquad [1]\end{aligned}$$

The amount of residue produced by other crops grown in rotation with corn was also calculated using crop-specific residue to grain ratios and bushel to dry mass conversion factors (Table 1). Estimates of other crop residues were used in the wind and water erosion constraint calculations for different rotations. County grain production and area harvested for 1995 through 2000 were obtained from the USDA National Agricultural Statistics Survey (USDA-NASS, 2003) and used to calculate an average grain yield by dividing the sum of the grain production over those years by the sum of the harvested acres.

Constraints to Stover Collection

To determine the amount of stover that could be collected (collectable stover), three constraints were considered.

Equipment Constraints

Collection operations leave some stover in the field. The amount left in the field is a function of the equipment used to collect the stover and the condition of the stover. For this analysis, it was assumed that at least 25% of the stover would be left in the field because of current equipment collection limitations; thus, no more than 75% of the stover could be collected under any condition (Montross et al., 2002; Schechinger and Hettenhaus, 2004). Working in experimental Kentucky fields, Montross et al. (2002) reported round bale collection efficiencies of 38%, 55%, and 64% using three strategies, respectively: bale only; rake and bale; and mow, rake, and bale. Schechinger and Hettenhaus (2004) reported collection efficiencies of 40 to 50% without raking and 70% with raking in large-scale stover collection operations in Nebraska and Wisconsin.

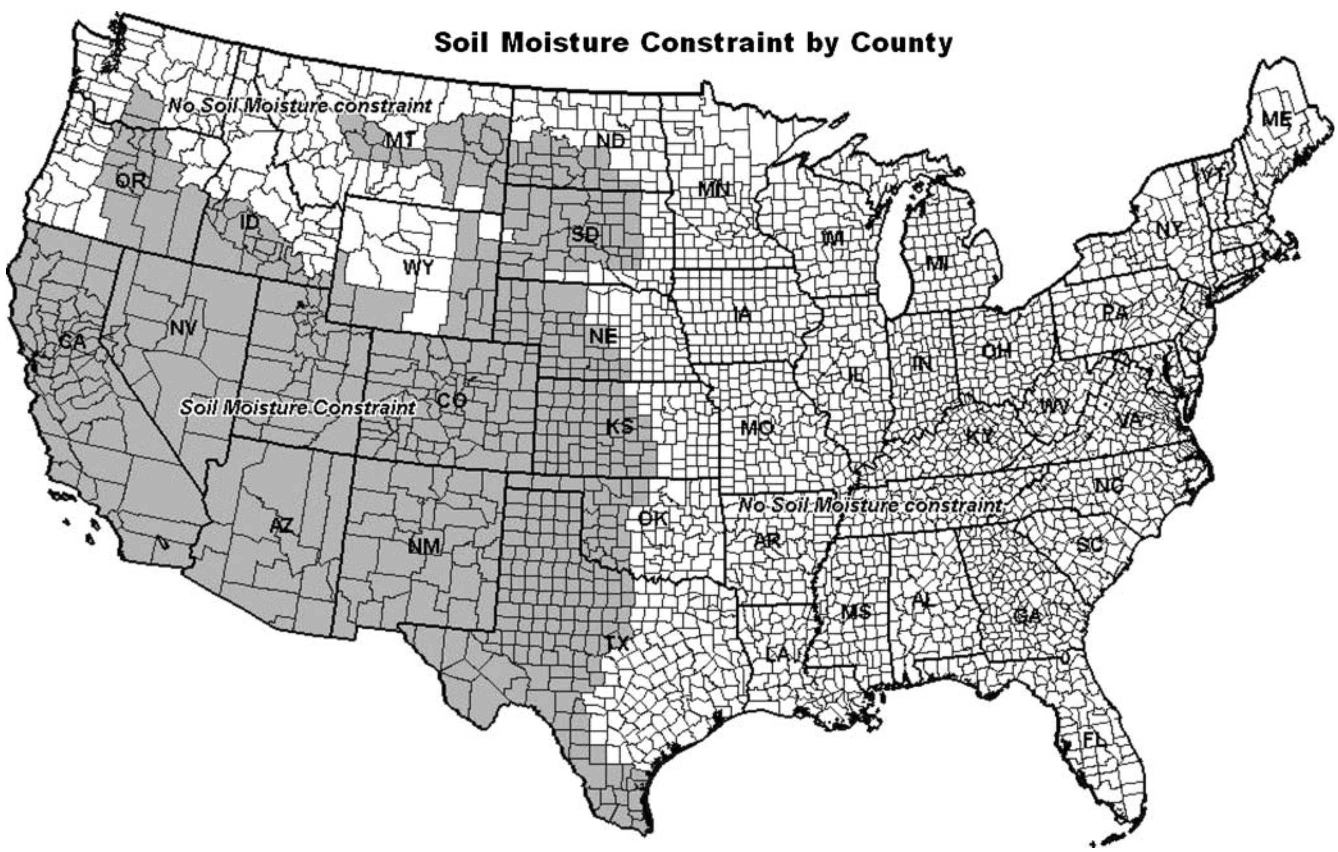


Fig. 1. U.S. counties where the need to leave stover to conserve soil moisture constrains all collection of stover except under irrigated corn production (based on Allmaras, 1983).

Soil Moisture Constraints

In some regions of the country, under rainfed agriculture all stover must be left on the field to maintain soil moisture for the next crop. Under the assumption that these regions coincide with where local wind erosion climatic factor is greater than 50 in April (R. Follette, personal communication, 2005), Allmaras' (1983) map of climatic factors was used to locate counties with a soil moisture constraint that precluded any stover collection (Fig. 1). This constraint was not applied to stover collection from irrigated corn production. Data from the USDA National Agricultural Statistical Survey (USDA-NASS, 2003) were used to determine area and yield of irrigated corn production in the counties where stover from rainfed corn production could not be collected (Fig. 2).

Water and Wind Erosion Constraints

The stover needed to remain in the field (Mg ha^{-1}) to assure that erosion did not exceed the tolerable soil loss value (T) was estimated using the approach of Nelson (2002), Nelson et al. (2004), and Sheehan et al. (2004). This approach considers cropping rotation, tillage, local climate conditions, and the suite of agricultural soil types found in a county. Only corn rotations that accounted for more than 15% of the hectares in corn production in the state were evaluated (Padgitt et al., 2000). Corn–corn and corn–soybean [*Glycine max* (L.) Merr.] rotations were evaluated for all states. Corn–small grain rotations (wheat [*Triticum aestivum* L.], barley [*Hordeum vulgare* L.], and oat [*Avena sativa* L.]) were also evaluated for North and South Dakota. Three tillage practices were considered for each rotation: conventional tillage (moldboard plow followed by disking and cultivation), mulch till (chisel disking followed by cultivation), and no-till production systems. For each combination of rotation and tillage practice, soil type-specific erosion constraint values were calculated and converted to a single county-level value by weighting all the soil type-specific values by their land area relative to the county's total cropland soil base. Water erosion constraints to collection were considered in all states east of the Rocky Mountains, and wind erosion constraints were considered only in the western states shown in Fig. 3.

Collectable Stover

For each rotation and tillage practice combination, the collectable stover (dry Mg ha^{-1}) was estimated by subtracting the maximum collection constraint from the amount of stover produced per hectare in the county.

$$CQ_{c,r,t} = \text{Stover}_c - \text{Max constraint}_{c,r,t} \qquad [2]$$

where CQ = collectable stover per ha in county c under rotation r and tillage t (Mg ha^{-1} yr^{-1}), c = county, r = rotation, t = tillage practice, Stover = the amount of stover produced per hectare in county c (Mg ha^{-1} yr^{-1}), and Max constraint = the amount of stover left in the field that meets all erosion, moisture, and equipment constraints in county c under rotation r and tillage t (Mg ha^{-1} yr^{-1}).

With the exception of counties with soil moisture constraints, stover production was calculated on the basis of all corn production in the county. In counties where soil moisture constrained collection of stover from rainfed corn production but corn was produced with irrigation, stover production was calculated on the basis of stover produced under irrigated corn production, and the soil moisture constraint and the water erosion constraint were not included in determining the maximum constraint value. Data from the National Agricultural

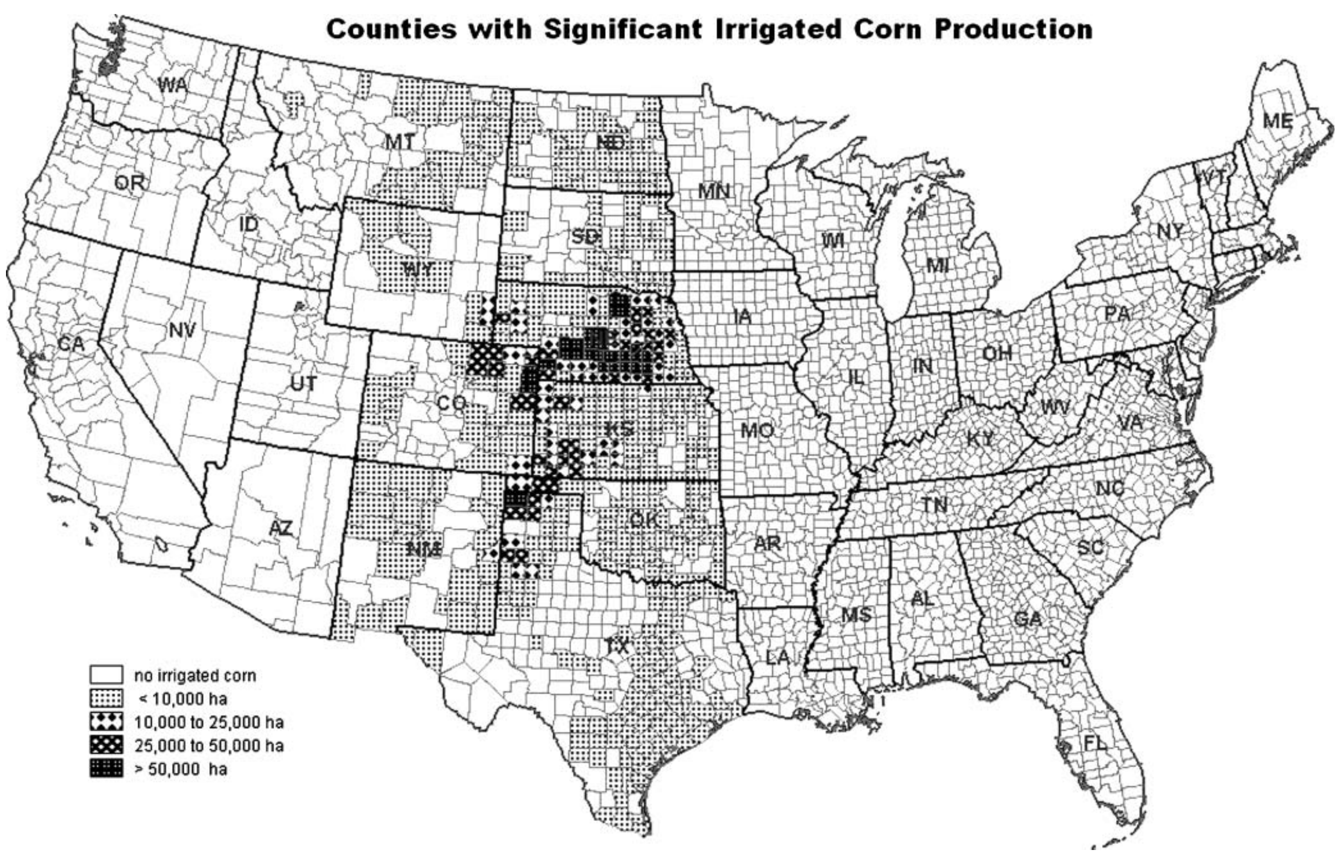


Fig. 2. U.S. counties with significant irrigated corn production (based on USDA-NASS, 2003).

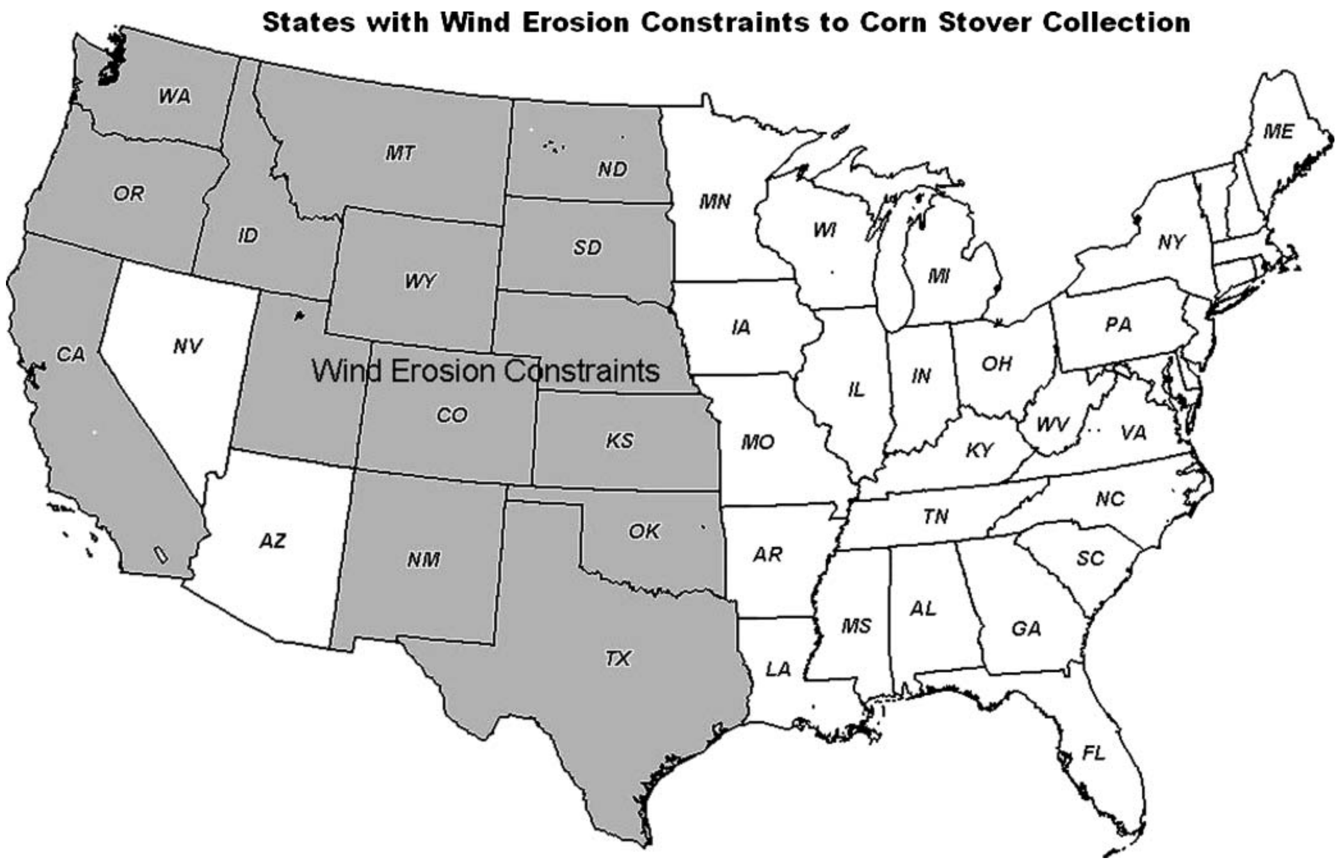


Fig. 3. States where wind erosion was considered as a constraint to stover collection.

Statistical Survey (USDA-NASS, 2003) were used to determine area and yield of irrigated corn production in the counties where stover from rainfed corn production could not be collected (Fig. 2).

Cost of Collecting Stover

The farmgate cost of collecting stover was calculated using an engineering approach (American Association of Agricultural Economics, 2002) and was based on the work of Perlack and Turhollow (2003), Sokhansanj and Turhollow (2002), and Sokhansanj et al. (2002). The costs are in 2002 dollars and reflect replacement of nutrients removed with the stover estimated at \$7.17 Mg^{-1} (\$6.50 ton^{-1}) (Gallagher et al., 2003) and all resources associated with collecting stover and delivering it to the side of the field in the form of large round bales, wrapped in mesh. Depending on the amount of stover to be collected, one of three collection scenarios was assumed (Table 2). For each collection scenario, collection costs were estimated for a range of stover collection quantities and a regression equation was developed that related collection costs with amount of stover collected (Fig. 4). These equations were used to associate a collection cost for each unique value of $CQ_{c,r,t}$.

Estimating County Stover Supply

Each county's supply (Mg yr^{-1} at a given cost) of collectable stover was calculated for the following four scenarios: (i) current tillage practices and constraining erosion to less than T, (ii) universal no-till and constraining erosion to less than T, (iii) universal mulch till and constraining erosion to less than T, and (iv) current tillage practices and constraining water erosion to less than 1/2 T (only calculated for states without wind erosion).

Current Supply and Erosion less than T

The following equation was used to estimate collectable stover for the first scenario:

$$S_{s,c,r,t} = CQ_{c,r,t} \times Land_c \times Tillage_{t,c} \times Rotation_{s,r} \quad [3]$$

where S = collectable stover supply in county c under rotation r and tillage t (Mg yr^{-1}), CQ = collectable quantity of stover under rotation r and tillage t in county c (Mg ha^{-1} yr^{-1}), Land = hectares of harvested corn in the county c (ha yr^{-1}), Tillage = % of corn under tillage scenario t in county c, and rotation = % of corn in rotation scenario r in state s.

Table 2. Collection scenarios as function of amount collected. Under all situations, bales are moved to the field edge for storage using a 89 kW (120 hp) tractor and bale wagon (Inland) with a capacity of 17 bales.

Amount of stover collected	Collection method
<2.69 dry Mg ha^{-1} (<1.2 dry tons $acre^{-1}$)	Turn-off combine spreader to create windrow, pick up windrow with round baler (89 kW [120 hp] tractor, round baler, megatooth pickup, push bar, surface wrap, crop processor)
2.69 to 3.36 dry Mg ha^{-1} (1.2–1.5 dry tons $acre^{-1}$)	Same as <2.69 dry Mg ha^{-1} except front-end wheel rake added to tractor
>3.36 dry Mg ha^{-1} (>1.5 dry tons $acre^{-1}$)	Two operations: flail shredding and raking followed by baling without crop processor (63 kW [85 hp] tractor, flail crop shredder, v-formation wheel rake followed by 63 kW tractor, megatooth pickup, push bar, surface wrap)

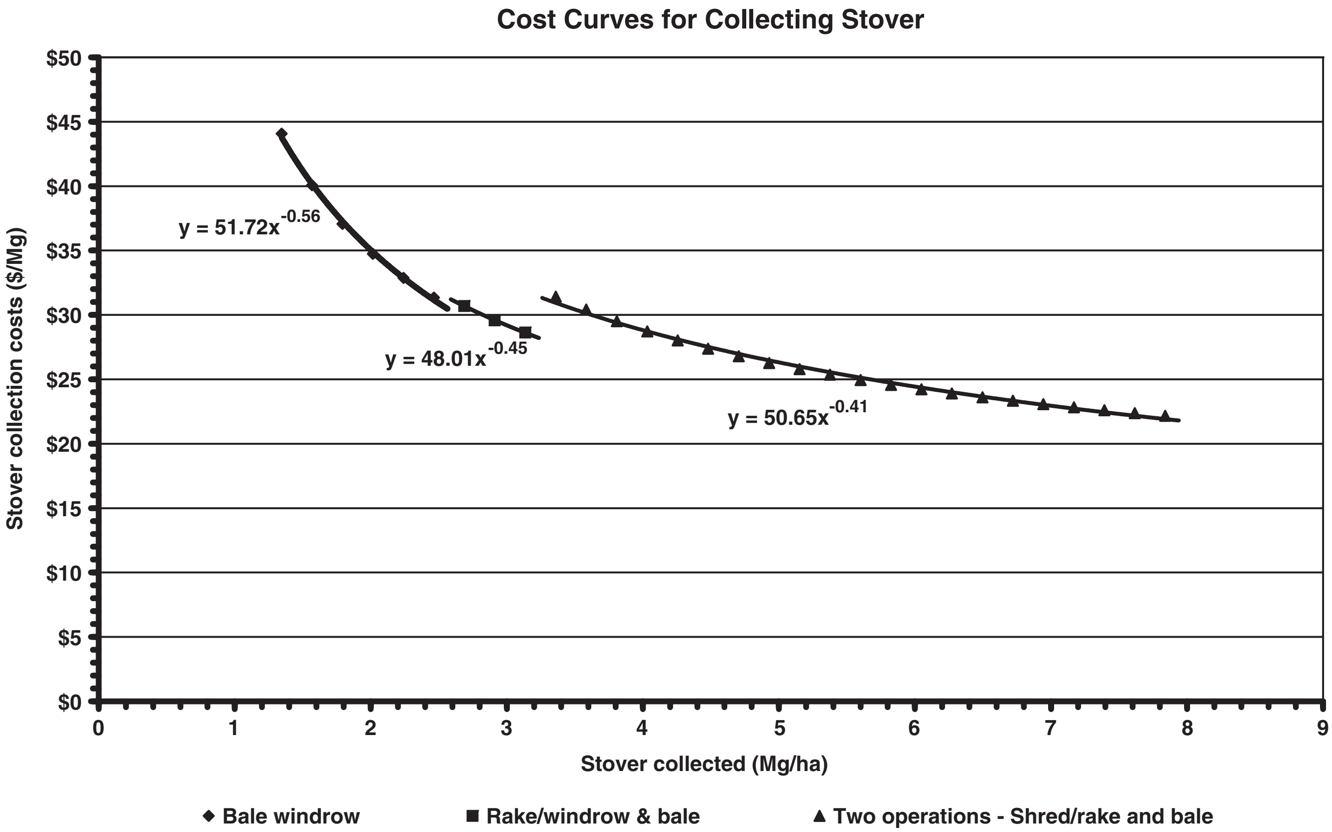


Fig. 4. Curves used to estimate stover collection cost as a function of stover collected in the field. Curves include \$7.17 Mg^{-1} nutrient replacement cost (\$6.50 ton^{-1}) (Gallagher et al., 2003). "Bale windrow" refers to the collection method assumed to be used when collecting less than 2.69 Mg ha^{-1}. "Rake/windrow & bale" refers to the method assumed used when collecting between 2.69 and 3.36 Mg ha^{-1}. "Two operations–Shred/rake and bale" refers to the method assumed used when collecting greater than 3.36 Mg ha^{-1}. The three methods are described in Table 2.

For this calculation, the value of $Land_c$ was based on harvested corn hectares in a county between 1995 and 2000 as reported by USDA (USDA-NASS, 2003). In counties with soil moisture constraints, only irrigated corn hectares were considered. The value of $Tillage_{t,c}$ was based on county-level data from the National Crop Residue Management Survey (CTIC, 2004) on corn tillage practices between 1995 and 2000. The Survey covers five tillage categories: conventional till, reduced till, ridge till, mulch till, and no-till. Conventional and reduced till hectares were grouped together to define corn produced under conventional tillage. Likewise, ridge and mulch till hectares were grouped to define corn produced under mulch tillage.

Collection costs associated with each $CQ_{c,r,t}$ were calculated using the regression equation. These costs were paired with their appropriate supplies ($S_{s,c,r,t}$), and the quantities of collectable corn stover available at farmgate costs less than \$27.56, \$33.07, \$38.58, and \$44.09 per Mg (\$25, \$30, \$35, and \$40 per ton) were calculated.

Potential Stover Supply under Universal No-Till or Mulch Till Practices

The impact of tillage practices was evaluated by estimating the supply of stover that could be collected if all current corn production was in no-till or mulch till. No change in yield was assumed. Equation [3] was used, but only no-till (or mulch till) values of CQ were considered, and Tillage was set to 100%.

Supply of Collectable Stover if Water Erosion Is Constrained to less than 0.5 T

To evaluate the impact of more stringent sustainability requirements, the amount of stover that must be left in the field under current tillage practices to assure that water erosion did not exceed 1/2 T was calculated. This was done for all rotations and tillage practices. CQ was recalculated taking into account the stover needed in the field under the more stringent constraint, and then S was calculated. This calculation was done only for states where wind erosion was not evaluated.

RESULTS AND DISCUSSION

The national supply of collectable stover is directly related to the quantity of grain produced. Figure 5 shows the amount of stover (196 million Mg) annually produced from corn grain production assuming ~196 million Mg of corn grain production (the average annual U.S. corn production between 1995 and 2000) and a stover HI of 0.5. To put this number in context, U.S. corn production from 1993 to 2005 has ranged from 136 to 254 million Mg yr^{-1} (6.3–11.8 billion bushels yr^{-1}) with an upward trend but significant year to year variation. Corn production exceeded 215 million Mg (10 billion bushels) in 1994, 2003, 2004, and 2005 but hovered between 194 and 213 million Mg between 1996

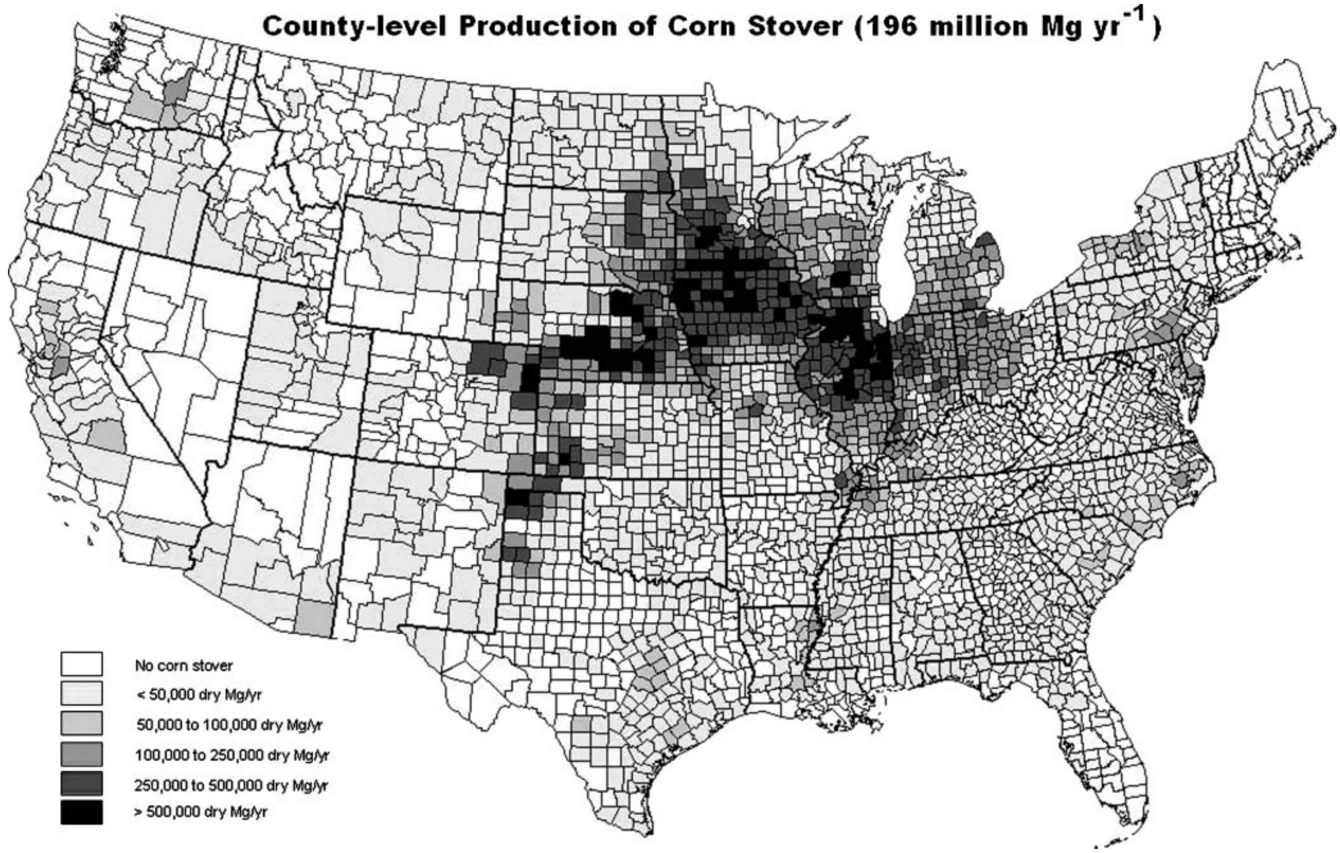


Fig. 5. Annual production of corn stover in the United States. Values were derived as described in text using 1995–2000 corn production statistics from USDA.

and 2002 and dropped to 159 million Mg in 1995 (USDA-NASS, 2006).

The amount of stover produced is influenced not only by corn grain production but also by the stover HI. Although the stover HI is commonly assumed to be 0.5 (i.e., 50% of the dry mass of the corn plant is grain and 50% is stover, the value used in this analysis), various reports applied the 0.5 HI but then used the weight of a bushel of #2 corn at 15.5% moisture rather than the dry weight to calculate the mass of stover per bushel of harvested corn grain. Failure to adjust for the water in the standard weight of #2 corn grain when computing stover production from grain production and stover HI results in inflated estimates of stover quantities. The use of stover HI to compute stover mass is problematic in that stover HI is variable. Linden et al. (2000) reported an average corn grain HI (grain dry weight to total plant dry weight) of 0.561 (SD = 0.079) or a stover HI of 0.439 for corn production over 14 yr in east central Minnesota. Montross et al. (2002) found a stover HI of 0.47 to 0.52 on a farm in Kentucky. Both studies reported that as grain yield went up, stover HI went down. Patterson et al. (1995) also noted variability in residue HI for wheat. This issue is important because it significantly affects the amount of stover that is estimated to be collectable regardless of what constraints to collection are assumed for meeting sustainability needs. It is also the source of some of the variability in estimates of collectible stover.

Stover Supply under Current Corn Production Practices

Given the constraints discussed previously, the total annual collectable stover in the USA was estimated at 58.3 million Mg (64.2 million dry tons). This value was nearly 30% of all stover produced. Nearly all the collectible stover (93%) came from land where at least 2 Mg of stover could be collected per hectare and collection costs were less than \$33.07 Mg^{-1} (\$30 ton^{-1}). More than half the supply of harvestable stover was from fields where 4 Mg ha^{-1} or more could be collected at a cost of less than \$27.56 Mg^{-1} (\$25 ton^{-1}) (Table 3). Most of the supply (62%) came from three major corn-producing states: Iowa, Minnesota, and Illinois. The supply from Nebraska, another major corn-producing state, was comparatively low because of the impact of wind erosion on collection, a constraint not considered in the other three states but likely to be critical in some areas of these states. Wind erosion constrained collection significantly. Wherever wind erosion was calculated, stover could be collected only from lands managed using mulch or no-till practices.

Figure 6 shows at a county level where 54 million Mg of stover could be collected for less than \$33.07 Mg^{-1} (\$30 ton^{-1}). Three regions stood out as suitable for stover collection in large quantities: central Illinois/Indiana, northern Iowa/southern Minnesota, and along the Platte River in Nebraska (Table 4). Table 3 characterizes these

Table 3. Hectares of harvested corn, quantities of collectable stover in Mg (000) by collection cost, and quantity of stover produced. The quantity of stover available at a cost >\$44.09 Mg^{-1} is the same as the total amount of collectable stover. Stover values are based on current corn grain production and management practices.

State	Corn	Stover <\$27.56 Mg^{-1}	Stover <\$33.07 Mg^{-1}	Stover <\$38.58 Mg^{-1}	Stover <\$44.09 Mg^{-1}	Stover >\$44.09 Mg^{-1}	Total stover produced
	ha (000)	Mg (000)					
Alabama	0	0	0	0	0	2	357
Arizona	13	0	0	0	0	0	120
Arkansas	57	21	27	28	28	34	366
California	89	0	0	0	0	0	776
Colorado	409	1	84	90	91	92	2 953
Connecticut	0	0	0	0	0	0	0
Delaware	62	207	243	243	243	243	388
Florida	22	1	2	2	2	3	96
Georgia	145	8	43	50	50	59	755
Idaho	19	0	0	0	0	0	151
Illinois	4 316	5 797	9 901	10 139	10 243	10 488	30 962
Indiana	2 240	2 726	5 186	5 388	5 476	5 629	15 343
Iowa	4 848	9 500	13 120	13 374	13 540	13 710	35 934
Kansas	1 076	7	335	403	525	597	7 969
Kentucky	476	0	30	45	57	64	2 890
Louisiana	157	0	51	58	61	63	915
Maine	0	0	0	0	0	0	0
Maryland	163	128	259	272	275	282	1 004
Massachusetts	0	0	0	0	0	0	0
Michigan	839	1 544	2 672	2 777	2 808	2 847	5 115
Minnesota	2 663	9 648	11 636	11 716	11 758	11 824	19 427
Mississippi	162	0	9	10	10	14	871
Missouri	972	348	498	524	533	575	6 138
Montana	6	0	0	0	0	0	42
Nebraska	3 334	1 786	4 806	5 224	5 407	5 564	23 525
Nevada	0	0	0	0	0	0	0
New Hampshire	0	0	0	0	0	0	0
New Jersey	33	0	0	0	0	1	179
New Mexico	32	0	8	8	9	9	292
New York	234	0	58	92	92	125	1 309
North Carolina	305	23	479	574	591	620	1 496
North Dakota	277	0	2	2	13	22	1 509
Ohio	1 301	170	2 483	2 550	2 565	2 617	9 014
Oklahoma	84	0	18	18	18	18	621
Oregon	12	6	10	10	10	11	113
Pennsylvania	407	0	16	35	49	80	2 260
Rhode Island	0	0	0	0	0	0	0
South Carolina	121	0	132	156	161	177	476
South Dakota	1 357	35	434	434	434	598	7 549
Tennessee	240	10	23	23	33	38	1 377
Texas	732	0	39	41	83	96	4 642
Utah	8	0	0	0	0	0	61
Vermont	0	0	0	0	0	0	0
Virginia	109	52	94	103	104	107	618
Washington	36	20	23	25	25	25	356
West Virginia	12	0	0	0	0	0	63
Wisconsin	1 189	292	1 383	1 482	1 550	1 632	8 076
Wyoming	21	0	0	1	1	1	137
USA	28 579	34 028	54 105	55 898	56 844	58 267	196 244

three regions. They have high corn yields, are flat, and, in the case of Nebraska, irrigated. Collection constraints require that at least a third of the stover be left on the field. Conservation tillage (mulch or no-till) is used on 22% of the central Illinois/Indiana land, 29% of the Iowa/Minnesota land, and 61% of the Nebraska land. These regions are capable of supporting biorefineries demanding large quantities of stover annually within a short hauling distance (USDOE-USDA 2002a).

The estimate of current collectable stover supplies is significantly less than previous estimates: 89.8 million Mg (98.9 million dry tons) (Gallagher et al., 2003) and 108.9 million Mg (120 million dry tons) (Walsh et al., 2000). The Gallagher et al. (2003) estimate was based on (i) a higher HI, (ii) all corn produced using mulch till practices, (iii) no equipment constraints to collection, and (iv) a minimum of 1.6 Mg ha^{-1} (0.72 tons acre^{-1}) of stover left on the field. Gallagher et al. (2003) estimated delivered bale costs generally less than \$16.53 Mg^{-1}. Their lower cost is attributable to lower assumed labor costs, the assumption that harvest costs were fixed per hectare, and the assumption that stover could be collected efficiently without raking. The Walsh et al. (2000) estimate assumed 25.4 kg of stover were produced per bushel (rather than 21.5 kg as in this study) and no equipment constraints to collection.

Effect of Increased Adoption of Conservation Tillage

Changing tillage management significantly affected the estimate of collectible stover, especially in western states where wind erosion is problematic (Fig. 7). Collectable stover in Nebraska more than doubled under the assumption of universal no-till corn production. If all U.S. corn production were under mulch till and if the

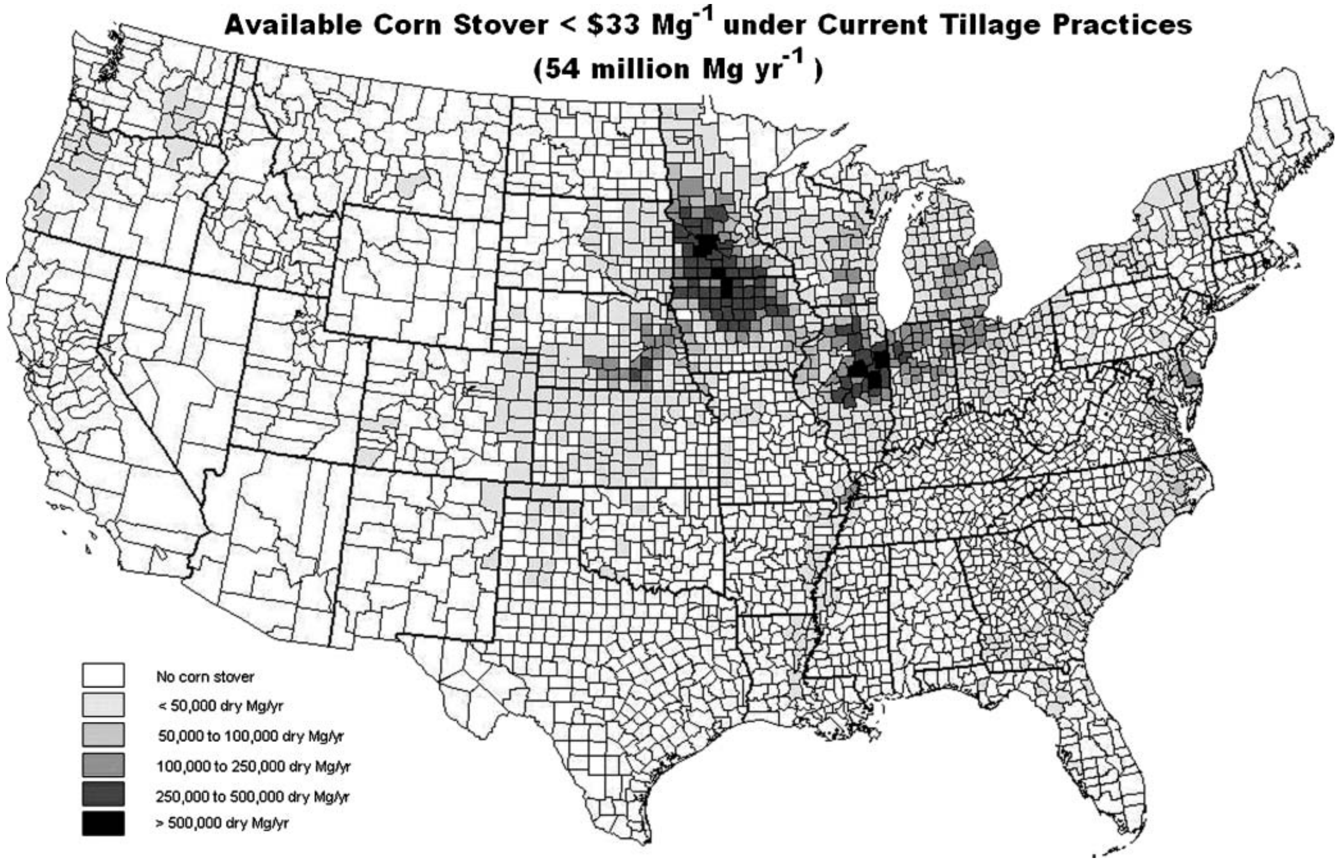


Fig. 6. Sustainably collectable corn stover for less than \$33.07 Mg^{-1} (\$30 ton^{-1}) under current (1995–2000) tillage practices.

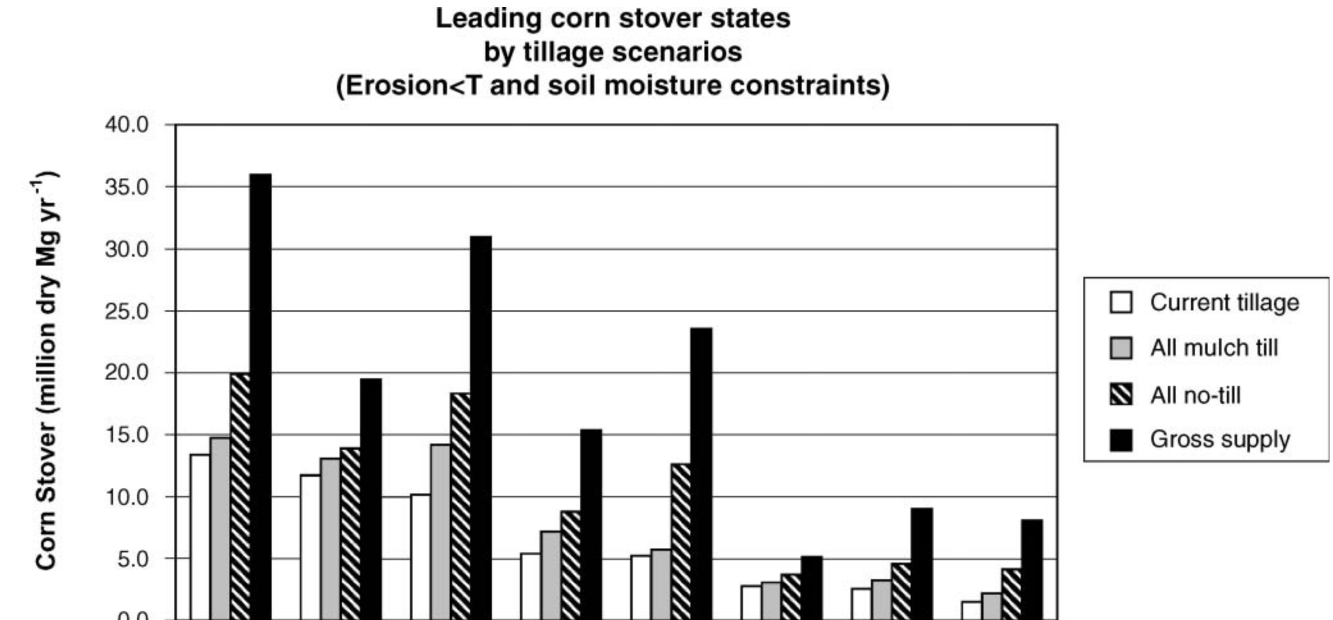
assumed annual corn production area of ~28.5 million hectares did not change, the total collectable stover supply (at any price) would rise to 68.9 million Mg (76 million tons yr^{-1}). Similarly, if no-till practices were universally adopted, the total collectable stover supply would increase to 101.2 million Mg (111 million tons). Even with these tillage practices, nearly 50% of stover would remain uncollectible. The location of sustainably collectable stover at less than \$33 Mg^{-1} (Fig. 8) showed almost no overlap with the 59 million hectares (146 million acres) of land classed as highly erodible cropland in 1997 by NRCS (Heimlich, 2003). This indicates that the highly erodible land, defined as land where the erosion potential is at least eight times its T value, would not be a source of sustainable stover biomass, even with no-till management. The additional stover under reduced tillage scenarios came from the highest corn yield production areas (compare Fig. 5 and 8) and moderately expanded the three regions previously identified as being suitable for large biorefineries (Fig. 6). Under no-till scenarios, the inability of equipment to collect more than 75% of the stover became the maximum constraint to collection in many areas.

Effect of More Restrictive Constraints on Water Erosion

If more stringent water erosion constraints were assumed (i.e., that stover could be collected only when removal would not increase erosion to more than 0.5 T), the collectable supply decreased significantly regardless of tillage assumptions (Fig. 9). Under this scenario (which addressed only states assumed not to have wind erosion constraints), only 22 of the 145 million Mg of stover produced in these states was available for collection. However, if universal no-till were adopted, the available stover would more than double to 57.5 million Mg per year. Although T is commonly assumed to be an acceptable erosion rate, it may not be sustainable (Mann et al., 2002). Thus, there is merit to exploring the impact

Table 4. Characteristics of the three major corn stover supply regions in the United States assuming current (1995–2000) corn management practices.

Region	No. of counties with >200 000 Mg yr^{-1} supply	Avg. corn yield	Supply <\$27.56 dry Mg^{-1}	Supply <\$33.07 dry Mg^{-1}	Percentage stover removal from the field	Stover left in field	Stover collected Mg ha^{-1} (tons acre^{-1})
		Mg ha^{-1} (bushels acre^{-1})	Mg 10^6 (ton 10^6)			Mg ha^{-1} (tons acre^{-1})	
Iowa–Minnesota	64	7.59 (143)	17.78 (19.6)	20.32 (22.4)	67.7%	2.45 (1.1)	5.16 (2.30)
Illinois–Indiana	29	7.40 (139)	6.08 (6.7)	9.25 (10.2)	60.6%	2.92 (1.3)	4.46 (1.99)
Nebraska–Platte River	6	7.59 (143)	1.27 (1.4)	1.36 (1.5)	41.4%	4.48 (2.0)	3.11 (1.39)



	IA	MN	IL	IN	NE	MI	OH	WI
Current tillage	13.4	11.7	10.1	5.4	5.2	2.8	2.6	1.5
All mulch till	14.7	13.1	14.2	7.2	5.7	3.1	3.2	2.2
All no-till	19.9	13.9	18.3	8.8	12.6	3.7	4.6	4.1
Gross supply	35.9	19.4	31.0	15.3	23.5	5.1	9.0	8.1

Fig. 7. Top eight states for producing collectable corn stover. Three tillage scenarios were considered: current tillage practices, universal mulch till, and universal no-till. Collection was constrained by soil moisture and equipment consideration and limiting erosion to less than tolerable soil loss.

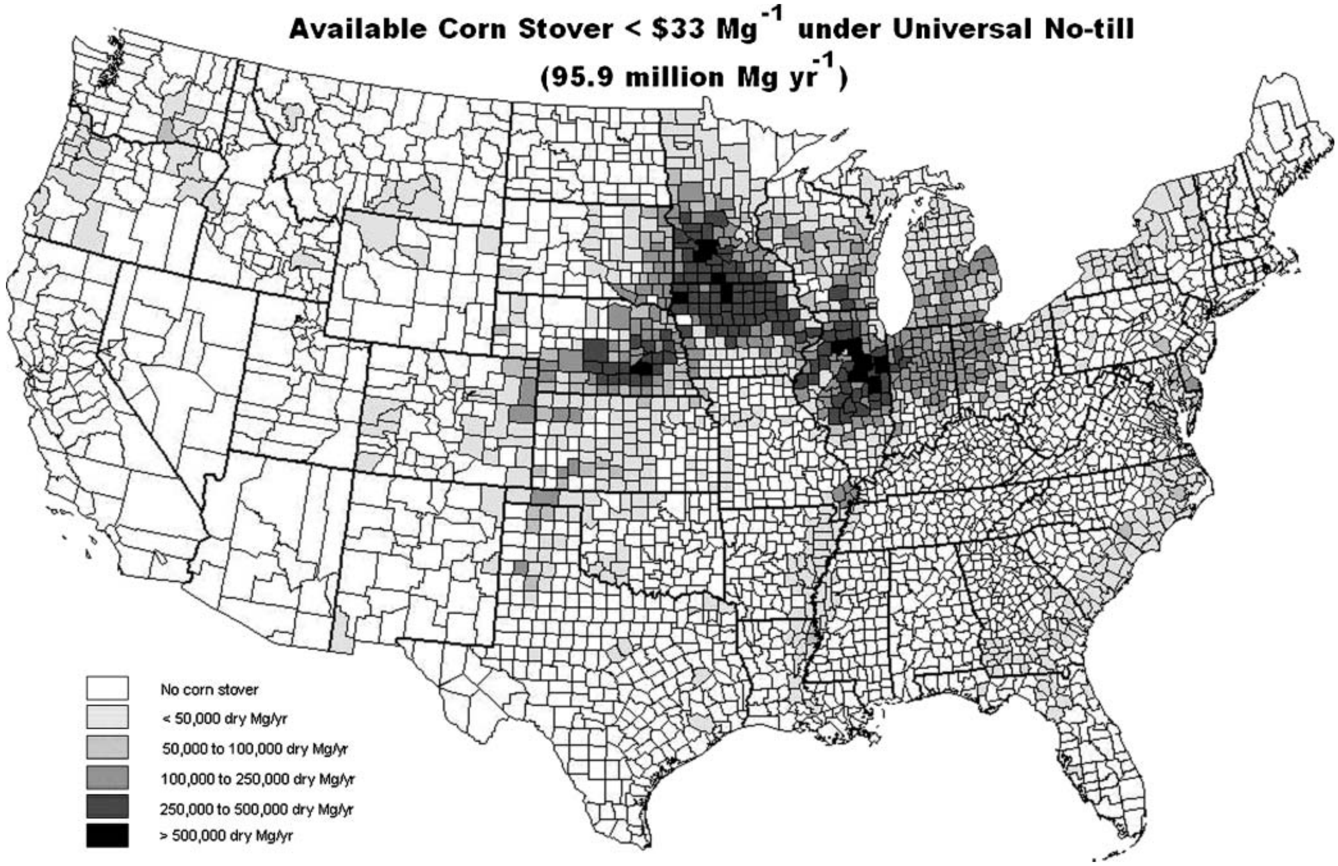


Fig. 8. Sustainably collectable corn stover for less than \$33.07 Mg^{-1} (\$30 ton^{-1}) assuming universal no-till corn production.

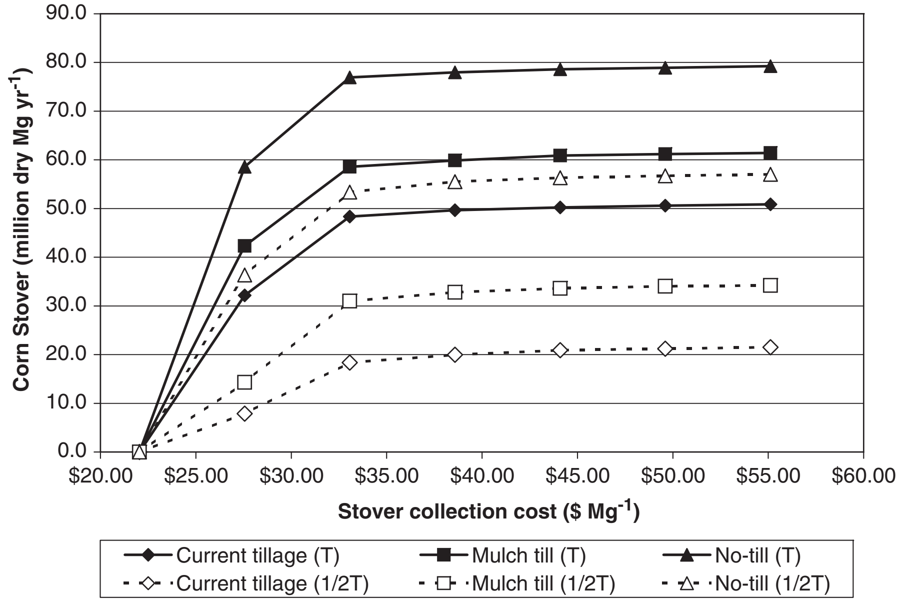


Fig. 9. Collectable stover from states without wind erosion considerations (see Fig. 3). Collectable stover was calculated as a function of differing combinations of water erosion constraints (limiting erosion to < tolerable soil loss [T] or less than 0.5 T) and tillage assumptions (current practices, universal mulch till, or universal no-till). Curves are cumulative over the cost range.

of more stringent erosion constraints on stover collection. Such constraints would also contribute to sustaining soil carbon.

SUMMARY

Given current corn production practices, less than 28% of the stover produced in the United States could be sustainably collected at a farmgate cost less than \$33.07 Mg^{-1} (\$30 dry ton^{-1}). More stringent soil loss constraints would lower this value considerably. However, if farmers chose to universally convert to no-till corn management and total stover production did not change, the sustainable supply would almost double. Given the current (1997–2000 average) U.S. corn production, 91.8 to 106.1 million Mg (105–117 million dry tons) of stover would be potentially collectable if farmers wished to manage their corn lands to produce harvestable grain and stover. These values have considerable uncertainty because they do not account for variation in stover HI and do not factor in the need to maintain or enhance soil organic matter and tilth. The latter consideration may require more stover left on site than was estimated in this analysis, which considered only soils erosion and soil moisture constraints. The estimate may also be high because current equipment may not be able to collect stover as efficiently as was assumed in this analysis. Nonetheless, they suggest that sufficient corn stover could be sustainably collected to support the development of corn-stover–based biorefineries in the Midwest.

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REFERENCES

American Association of Agricultural Economics. 2002. Commodity costs and returns estimation handbook. Available at www.economics.nrcs.usda.gov/care/Aaea/ (accessed 12 Feb 2003; verified 27 Aug. 2006). AAAE, Blackland Research Center, Texas A&M Univ., Temple, TX.

Allmaras, R.R. 1983. Soil conservation: Using climate, soils, topography, and adapted crops information to select conserving practices. p. 139–153. *In* H.E. Dregne and W.O. Willis (ed.) Dryland agriculture. Agron. Monogr. 23. ASA, CSSA, SSSA, Madison, WI.

Conservation Technology Information Center. 2004. National crop residue management survey conservation tillage data. Available at www.conservationinformation.org/?action=crm (accessed 12 Feb 2002; verified 27 Aug. 2006). Purdue Univ., West Lafayette, IN.

Gallagher, P., M. Dikeman, J. Fritz, E. Wailes, W. Gauther, and H. Shapouri. 2003. Biomass from crop residues: Cost and supply estimates. USDA, Office of the Chief Economist, Office of Energy Policy and New Uses. Agricultural Economic Rep. 819. USDA, Washington, DC.

Gupta, S.C., C.A. Onsted, and W.E. Larson. 1979. Predicting the effects of tillage and crop residue on soil erosion. J. Soil Water Conserv. Spec. Publ. 25:7–9.

Heimlich, R. 2003. Agricultural resources and environmental indicators, 2003. USDA ERS. Available at www.ers.usda.gov/publications/arei/ah722 (accessed 21 July 2004; verified 27 Aug. 2006). Agricultural Handb. AH722. USDA-ERS, Washington, DC.

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

Mann, L., V. Tolbert, and J. Cushman. 2002. Potential environmental effects of corn (*Zea mays* L.) stover removal with emphasis on soil organic matter and erosion: A review. Agric. Ecosyst. Environ. 89:149–166.

Montross, M.D., R. Prewitt, S.A. Shearer, T.S. Stombaugh, S.G. McNeil, and S. Sokhansanj. 2002. Economics of collection and transportation of corn stover. ASAE Paper 036081 presented at the Annual International Meeting of the American Society of Agricultural Engineers, Las Vegas, NV. 27–31 July 2003. ASAE, St. Joseph, MI.

Nelson, R.G., M. Walsh, J.J. Sheehan, and R. Graham. 2004. Methodology for estimating removable quantities of agricultural residues for bioenergy and bioproduct use. Appl. Biochem. Biotechnol. 113:13–26.

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

Padgitt, M., D. Newton, R. Penn, and C. Sandretto. 2000. Production practices for major crops in U.S. Agriculture, 1990–97. Statistical Bulletin 969. Resource Economics Division, USDA-ERS, Washington, DC.

Patterson, P., L. Makus, P. Momont, and L. Robertson. 1995. The availability, alternative uses and value of straw in Idaho. Report to the Idaho Wheat Commission, Project BD-K251. Available at www.ag.uidaho.edu/aers/r_project_reports.htm (accessed 13 June 2003; verified 27 Aug. 2006). Univ. of Idaho, College of Agricultural and Life Sciences, Moscow, ID.

Perlack, R.D., and A.F. Turhollow. 2003. Feedstock cost analysis of corn stover residues for further processing. At. Energy 28:1395–1403.

Schechinger, T.M., and J. Hettenhaus. 2004. Corn stover harvesting: Grower, custom operator, and processor issues and answers—report on corn stover harvest experiences in Iowa and Wisconsin for the 1997–98 and 1998–99 crop years. ORNL/SUB-0404500008274-01. NTIS, Springfield, VA.

Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelson. 2004. Energy and environmental aspects of using corn stover for fuel ethanol. J. Ind. Ecol. 7:117–146.

Sokhansanj, S., and A.F. Turhollow. 2002. Baseline cost for corn stover collection. Appl. Eng. Agric. 18:525–530.

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

USDA-NASS. 2003. Agricultural statistics data base (quick stats). Available at www.nass.usda.gov (accessed 15 May 2003; verified 27 Aug. 2006). USDA-NASS, Washington, DC.

USDA-NASS. 2006. Data and statistics/quick stats. Available at www.nass.usda.gov/Data_and_Statistics/Quick_Stats/index.asp (accessed 28 Feb. 2006; verified 27 Aug. 2006). USDA-NASS, Washington, DC.

USDA-NRCS. 2003. White paper: Crop residue removal for biomass energy production: Effects on soils and recommendations. Available at http://soils.usda.gov/sqi/management/files/AgForum_Residue_White_Paper.pdf#search=%22usda%20nrcs%20white%20paper%20residue%22 (accessed 12 July 2003; verified 18 Sept. 2006). USDA-NRCS Soil Quality Institute, Ames, IA.

USDA-NRCS. 2006. The soil conditioning index SCI. Available at http://soils.usda.gov/sqi/assessment/sci.html (accessed 12 July 2005; verified 27 Aug. 2006). USDA-NRCS, Washington, DC.

USDOE. 2003. Biomass program multi-year technical plan. Office of the Biomass Program in Office of Energy Efficiency and Renewable Energy. Available at www1.eere.energy.gov/biomass/pdfs/mytp.pdf (accessed 30 July 2006; verified 27 Aug. 2006). DOE-EERE, Washington, DC.

USDOE-USDA. 2002a. Roadmap for biomass technologies in the United States. Biomass Research and Development Technical Advisory Committee. Available at www.biomass.govtools.us/pdfs/FinalBiomassRoadmap.pdf (accessed 30 July 2005; verified 27 Aug. 2006). DOE-EERE, Washington, DC.

USDOE-USDA. 2002b. The vision for bioenergy & biobased products in the United States. Biomass Technical Advisory Committee. Available at www.biomass.govtools.us/pdfs/BioVision_03_Web.pdf (accessed 30 July 2006; verified 27 Aug. 2006). DOE-EERE, Washington, DC.

Walsh, M.E., R.L. Perlack, A. Turhollow, D.G. de la Torre Ugarte, D.A. Becker, R.L. Graham, S.E. Slinsky, and D.E. Ray. 2000. Biomass feedstock availability in the United States: 1999 State Level Analysis. Available at http://bioenergy.ornl.gov/resourcedata/index.html (accessed 14 July 2003; verified 27 Aug. 2006). Oak Ridge National Lab., Oak Ridge, TN.

Wilcke, W., and G. Wyatt. 2002. Grain storage tips: Factors and formulas for crop drying, storage and handling. Univ. of Minnesota Extension Service. Available at www.extension.umn.edu/distribution/cropsystems/M1080-FS.pdf (accessed 14 June 2004; verified 27 Aug. 2006). Univ. of Minnesota Extension Service, St. Paul, MN.

Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden. 2004. Crop and soil productivity response to corn residue removal: A literature review. Agron. J. 96:1–17.