THE VIABILITY OF CORN COBS AS A BIOENERGY FEEDSTOCK

by

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Abstract

Concerns about global climate change, air quality, and volatility in the fossil fuel market the have brought about renewed interest in alternative fuels. Interest has been partially focused on the biomass sector as a source of fuel for renewable energy production. In addition to other agricultural residues, the use of corn cobs as a biomass feedstock offers promising possibilities for renewable energy production. Recognizing this potential, this literature review summarizes publications and presents issues with the feasibility and sustainability of using corn cobs as an energy feedstock. The topics covered in this paper are: suitability of corn cobs as a bioenergy fuel; estimation of annual U.S. corn cob production; logistical issues associated with collection and storage; and uses of corn cobs as energy feedstock. With current corn production, 33.5–44.6 million metric tons of corn cobs are annually available for harvest. Potential issues with removal - nutrient removal, soil organic carbon depletion, and soil erosion - and utilization - logistical issues - of cobs are covered. Advantages of cob collection over other forms of biomass are also discussed in this review.

Introduction

The production and consumption of increasingly large amounts of energy are sustaining the U.S. modern standard of living. With few exceptions, fossil fuels have been a reliable and inexpensive feedstock for energy production. However, with a finite supply, current market volatility, and environmental concerns, fossil fuels do not emerge as the solitary solution for the world's future energy needs. Recently, there has been increased interest and research in the bioenergy sector for development of new, long-term energy sources. Bioenergy is a broad classification of energy production methods which utilize the physical and chemical properties of biomass - renewable plant-derived organic matter. These biomass materials include dedicated energy crops, agricultural residues, forestry wastes, aquatic vegetation, and municipal wastes. While there are numerous types of biomass, certain characteristics make some biomass materials more desirable for energy production. Energy density, moisture content, chemical composition, particle size, production rate, and sustainable production of the feedstock are all factors that should be considered in the selection of a desirable biomass feedstock.

Crop residues have potential to be utilized for bioenergy production. Annually approximately 204 million dry metric tons of corn residue are returned to the ground as waste byproduct in corn grain production (Perlack, R.D., *et al.* 2005). While corn stover, the above ground corn plant excluding corn kernels, has much potential in use as a biomass feedstock (Graham, R.L., *et al.* 2007), there are concerns associated with its removal from the ground. Crop residue removal contributes to soil organic matter and nutrient depletion (Follett 2001; Wilhelm, W.W., *et al.* 2004). Soil organic matter levels are related to many productive soil characteristics and are associated with continued crop production potential (Reicosky and Forcella, 1988). Soil organic matter levels also affect soil water infiltration, water holding capacity, and aeration (Wilhelm, W.W *et al*,. 2004). Crop residues are also important as top cover on agricultural land. Residues can act as buffers to falling rain and wind sheer that dislodge soil particles and cause erosion. Sun radiation, heat flux, and moisture evaporation are also affected by crop residue levels (Wilhelm, W.W., *et al.*, 2004). The removal of crop residue should be balanced against the environmental impact (soil erosion), maintenance of nutrient and soil organic matter levels, and preservation of productivity levels (Wilhelm, W.W., *et al.* 2004). These concerns associated with corn stover collection can be mitigated with partial stover collection.

While corn cobs have been used on a small scale as a fuel for direct combustion in cooking and heating, their use as feedstock for large-scale energy production is a more modern concept. The large-scale use of corn cobs presents new challenges and issues to consider: production rates must be estimated: harvesting, handling and storing methods should to be developed: effects of corn cob removal on soil composition and productivity should be assessed: and energy conversion methods must be optimized. This paper summarizes research done as literature review and addresses the above issues in order to determine the suitability and diversity of corn cobs in the bioenergy industry.

Energy Content

A feedstock used in bioenergy conversion must have adequate energy content. Energy content of feedstock can be given as an energy density measurement - energy per unit volume or weight. The volumetric energy density of an energy feedstock is significant when considering the volume of biomass needed to be harvested, transported, stored, and utilized in an energy production process. The higher the energy density, the less volume of biomass needed to produce a given amount of energy. While corn cobs are not as energy dense as the fossil fuels that society is familiar with, they have a similar energy density to other biomass feedstock and less energy dense coals, both of which are successfully utilized as energy feedstocks around the world. For comparison, the volumetric and mass energy densities of several feedstocks are given here on dry basis.

Fuel	Corn Cobs	Corn Stover	Switchgrass	Wood Pellets	Bituminous Coal	#2 Fuel Oil
Energy Content (MJ/kg)	18.25-19.18	17	18	19	25.5	43.5
Energy Content (MJ/m³)	4960-5210	2550	2500	12400	17,200-23,300	38,600

Table 1. - Sources: Clark, T.T. and Lathrop, E.C.; Foley, K.M.; Powder and Bulk; Mclaughlin, S.B., *et al.*; EIA-DOE

It should be emphasized that the energy content of corn cobs is given here in MJ/kg dry matter. Corn cobs are not harvested, stored, or utilized in a moisture free condition. Therefore, the actual energy densities of corn cobs, as with all forms of biomass, should be adjusted to compensate for the moisture content. For instance, at 20% moisture, a kg of cobs would cobs would have a higher heating value of 14.6-15.3 MJ. It should also be stated that the wood pellets in the above table have higher mass and volumetric energy content due to pelletization. This process, while increasing the density of the product, requires additional energy and equipment. The net result is increased cost of production and a reduction of the product's net energy. Corn cobs are sufficiently dense and therefore do not require densification.

Composition and Conversion

The chemical properties and physical characteristics of corn cobs make for a feedstock suitable for several methods of energy generation. A group of studies (Clark, T.F. and Lathrop E.C., 1953; Foley, K., 1978) found that corn cobs contain 32.3-45.6% cellulose, 39.8% hemicelluloses - mostly composed of pentosan, and 6.7-13.9% lignin. Cellulose is a polysaccharide of glucose units that serve as the main structural component of the cob's cell walls. Hemicellulose is a less complex polysaccharide that can more easily be broken down to simpler monosaccharides, simple sugars. Lignin is a complex, non-carbohydrate, structural component which binds to cellulose and stiffens plant cell walls.

Current and experimental processes are available to convert the energy contained in the corn cob molecular structure. Thermochemical conversion technologies such as combustion and gasification can utilize the molecular structure of the cellulose, hemicellulose, and lignin present in cobs to produce heat energy and/or synthesis gas. In direct combustion, corn cobs are completely combusted in an oxygen rich environment to produce heat energy. Direct combustion heating processes could either be fueled exclusively with corn cobs or co-fueled with coal. The benefits of using corn cobs as a partial coal substitute include a potentially cleaner emissions stream and the reduction of undesirable emissions and waste ash (Gani, A. and Naruse, I., 2007). The process of gasification uses high temperatures and an oxygen deficient environment to create a lower energy producer gas that can be used similarly to natural gas. Gasification allows for a more controlled partial combustion process and reductions in undesired emissions when compared to direct combustion.

Experimental cellulosic ethanol production - a type of biochemical conversion - is being researched to develop a process of converting the cellulose and hemicellulose portions of plant matter into ethanol. The cellulose and hemicellulose in cobs are hydrolyzed, broken down into simple sugars, and then fermented into alcohol. These processes can be impeded by variations; for this reason consistent, uncontaminated corn cobs appear to be a desirable feedstock. The use of cobs in cellulosic ethanol production creates an identical alternative to grain produced ethanol and reduces dependence on corn grain.

Production

Corn grain is the U.S.'s largest acreage crop with an averaged annual harvest of 73 million acres over the past 10 years (1998-2007). (USDA-NASS) At harvest, corn cobs have primarily been returned to the ground as crop residue. The implementation of a cob collection practice would allow for the production of desirable feedstock without the need for development of new crop production methods.

An estimation of the potential size of a corn cob harvest is needed to understand future potential as a bioenergy feedstock. The figures used for this estimation are the annual corn grain production, stover to grain ratio, and stover composition. A recent increase in the demand and price of corn has created an upward trend in corn production. Increased acreage and improvements in technology have increased the volume of recent corn harvests. The ability to maintain these harvest volumes is uncertain; consequently a conservative estimation of corn grain production will use a ten year average. A ten year average (1998-2007) should not neglect technology advancements while averaging the recent upward trends in corn production. The 10 year averaged U.S. corn production is 10.4 billion bushels or 264 million metric tons (USDA-NASS). For simplification in later calculations, the estimated wet mass of the corn harvest will be converted to dry mass. A shrink factor is used to account for mass loss due to moisture reduction. The shrink factor of 1.000 is determined by the final dried grain moisture content - zero percent (Hicks, D.R. and Cloud, H.A., 1992). Multiplying the shrink factor by the decreased moisture percentage gives a reduction in grain mass of 15.5%. Applying the moisture mass reduction, the annual corn harvest dry mass is found to be 223 million metric dry tons.

The estimation of annual corn stover production will continue using the stover to grain ratio. The stover to grain ratio is the relationship of total above ground plant matter - excluding grain - to grain matter (on dry basis). The stover to grain ratio has generally been accepted to be 1:1 (Graham, R.L., *et al.,* 2007); therefore, on average, an equal amount of corn grain and stover are produced. Technological changes such as corn cultivar variations and growing conditions should be considered when working with the stover ratio. A 13 year east central Minnesota study (Linden, D.R., *et al.,* 2000), found a correlation between an increased corn yield and a decreased stover to grain ratio. The study included various methods of tillage, residue management, fertilizer treatments, and weather conditions which provided for a diverse sample group. The study found that the stover to grain ratio decreased from 1.5:1 to 0.66:1 as yields increased to a maximum of

15 Mg/ha (239 bu/acre) (Linden, D.R., *et al.*,2000). Consequently, projections of increased stover yields that rely on an increased grain yield and a 1:1 ratio should also be used with caution until more data can be collected on the plant composition of higher yielding corn cultivars. For simplifying examples and arguments to generally representative values, this study will assume the stover to grain ratio to be 1:1 resulting in an average annual stover production of 223 million metric tons.

Studies on corn stover composition found that corn cobs make up 15-20% of corn stover (Meyers, D.K. and Underwood, J.F.; Payne, F.A., *et al*., 1980; Sokhansanj, S., *et al.*, 2002; Hanway, J.J., 2007). Based on the 15-20% of stover that is cobs, the U.S. annual corn cob production is estimated at 33.5-44.6 million metric tons. Due to complexities and uncertainties introduced with the sustainability and efficiencies of corn cob harvest, the above estimate is only a calculated best guess of possible cob production and not representational of a marketable cob volume.

Sustainable Production

Bioenergy feedstock should be sustainably produced in order to act as a long-term energy source while minimizing negative impacts. Corn residue collection for the production of bioenergy is feasible within limits. (Wilhelm, W.W., *et al.,* 2004) To verify the sustainability of cob collection, the ramifications of corn cob removal need to be thoroughly explored. Crop residues play an important role in the maintenance of soil productivity. Residues provide a buffer to wind shear and raindrop impact that leads to soil erosion. Residue also aids in the maintenance of soil organic matter, soil organic carbon, and nutrient levels - all desirable characteristics of productive soil.

Sustainable removal rates of agricultural residues, including corn cobs, are highly location dependent. The climate, geography, and management of land are all factors in the calculation of the amount of biomass able to be removed sustainably. Climatic parameters (e.g., annual rainfall, rainfall rates, and wind frequency and velocity), as well as geographic features (e.g., terrain and soil types), and human influences (e.g., tillage practices, crop rotations, and crop yields) all contribute to requiring the guidelines of residue removal be viewed on an individual site basis. Sites with steep grades, dry climates, and/or highly erodible soils produce much less and in some cases no removable organic matter due to their increased susceptibility to erosion. Studies on wind and soil erosion have resulted in the construction of the revised wind erosion equation (RWEQ) (Fryrear, D.W., *et al.*, 2001) and the revised universal soil loss equation (RUSLE) (Nelson, R.G., *et al.*, 2004), two models used to predict the amount of removable residue when maintaining acceptable soil erosion rates that will not lead to prolonged soil deterioration. These models take into account individual site characteristics (e.g., soil erosivity, soil erodibility, ground slope, crop yield and several management factors such as crop rotation and tillage practices) and create guidelines for keeping soil erosion at maintainable levels, but do not take into account the role of crop residue in maintenance of productive soil.

Crop residue strongly influences soil characteristics. Soil surface residue affects penetration of solar radiation, soil energy flux, retention of soil moisture. When reincorporated into soil, residue aids in the maintenance of soil nutrients, soil organic matter, and soil organic carbon. These factors make crop residue retention essential in varying degrees. The removal of a portion of residue from wet and cold climate soils may aid crop production due to higher spring time soil temperatures and the reduction of excess moisture. However, in dry and hot climates, complete residue retention may be required for the preservation of soil moisture and reduction of soil erosion.

When considering the role of crop residue in maintenance of soil productivity, corn cob collection for bioenergy generation offers advantages. Collection of corn cobs - 15-20% content of corn stover - allows for the remaining stover to be returned to the ground for top cover, soil organic matter replenishment, and nutrient replacement. Although much is known about the role of crop residue in retention of soil productivity, additional research is needed to determine the long-term effect of corn cob removal and to construct guidelines for sustainable corn cob removal.

The low nutrient content of corn cobs add to the potential sustainable use as a feedstock. The low nutrient content of corn cobs reduce the amount of nutrients removed with cobs at harvest which later need to be replaced to maintain soil nutrient levels (see tables 1-4). Commercial fertilizers, the predominant method of soil amendment, have increased in price by approximately 400% from April 2002 to August 2008. (USDA-ERS) The current fertilizer market volatility and possible future price increases have made nutrient replacement cost a necessary consideration for sustainable biomass production. A study done at Iowa State University presented the nutrient content of all parts of the corn plant (Hanway, J.J., 2007.). Using this data and current summer of 2008 fertilizer (nitrogen, phosphorus, and potassium) prices, the cost of macronutrient replacement was calculated for grain, cob, and stover harvest at a grain yield of 161 bu/acre. The low nutrient content of corn cobs resulted in a much lower cost of macro-nutrient replacement when compared to grain and stover (See table 4). The reduced cost of nutrient replacement for cob collection allows for greater profit potential in feedstock collection. The profit potential will become more significant with increased fertilizer prices.

Harvest

Corn cob collection methods may contribute to the viability of their use as bioenergy feedstock. Experimental harvesting methods may utilize a one-pass simultaneous collection of grain and cobs and should not significantly affect corn harvest rates. Two methods of cob collection are currently in experimental use. One method involves the collection of corn kernels and cob pieces together. After harvest, the mixture can be fed into a separator that sorts the grain and cobs. This method requires additional time and equipment to separate the cob pieces from the grain and may be unattractive during the busy grain harvest season. The other method involves the use of experimental attachments that utilize pneumatic and/or physical means to separate corn cobs from stover prior to ejection from the combine. This method does not affect the initial corn grain separation and therefore does not require additional post harvest sorting. The cobs can be collected in a wagon pulled behind the combine or in a separate hopper attached to the combine (see figures 2-5). With either method, the cobs and grain could be unloaded relatively quickly as to not slow the harvest rate. Once the cobs are unloaded, they can be piled at fields ends for temporary storage. The one-pass methods described here have several advantages over conventional biomass collection. One-pass cob collection requires less equipment, labor and passes over the field than baling methods. The reduction in field passes reduces additional soil compaction, a concern for later soil productivity. Advantages also are present in the fact that the corn cobs are collected directly out of the combine. The feedstock produced from cob harvest is for the most part free from contaminants such as dirt and rocks which could present challenges for bioenergy production.

Moisture and Storage

The moisture content of corn cobs can pose challenges in storage and use for energy conversion. Corn cobs are generally harvested with moisture content in the range of 20-50% which depends on the corn cultivar characteristics and harvest conditions (e.g. recent weather and date harvested). The high side of the range poses potential issues with storage and immediate use for energy production. Cobs with 10% to 30% moisture content are ideal for energy production; however, the range can vary depending on the production process. Cob moisture content has been found to be a critical factor in long term storage. A study done by R.D. Smith (Smith, R.D. *et al.,* 1985) examined the outside storage of corn cobs. Corn cobs were stacked in piles with varying initial moisture values of 28.0-38.5%. The piles were stored eight to nine months (winter to summer) and either ventilated with ambient air or left unventilated. Despite being outdoors and subjected to precipitation, the piles' interiors all decreased in average moisture content. The ventilated piles had the lowest interior moisture percentages at 9.1%, 15.1%, and 18.4%, while the unventilated piles had higher values of 23.6%, 25.4%, and 25.5%. Dry matter loss of the piles was associated with high moisture content which allowed for microbial activity and decomposition of corn cobs. The piles' outer layers experienced the highest dry matter loss - up to 29% - and had moisture contents ranging between 60% and 80%. The outer layer matter loss was unavoidable due to precipitation and weather conditions that caused high pile moisture content.

Ambient air ventilation proved to be advantageous for reducing cob spoilage. Ventilation allowed for quicker reduction of interior moisture and in turn reduced the cob dry matter loss. Mold growth, evidence of cob deterioration, was present in all smaller scale piles except the ventilated pile. The importance of ventilation was enforced by Dunning who stated that pile ventilation was important for the reduction of high corn cob moisture due to the lack of moisture change in non-ventilated piles. (Dunning *et al.,* 1948) Although these studies showed that ventilation improved cob storage, further research should be done to determine if the reduction in cob spoilage offsets the cost of electricity and equipment needed for pile ventilation.

Corn cob use as an energy feedstock requires large amounts of storage area. The seasonality of corn cob production and the year round operation of energy conversion facilities require the storage of at least one year's worth of feedstock. Storage area is dependent on the energy production plant's feedstock consumption rate, the larger the plant the more storage needed. For representative purposes, the storage requirements of the district heating gasification plant on the University of Minnesota, Morris are presented. The estimated requirement for annual operation of the gasifier is 9,000 tons of biomass - relatively small when compared to larger energy production plants. Assuming a cob bulk density of 272 kg/m^3 (17lb/ft^3) (Powder and Bulk) and a pile angle of repose of 36^o, (Smith, R.D., *et al.*, 1985) the storage area necessary for the plant's year long operation can be seen in table 6 and figure 1. Storage area is highly dependent on the piling method. A single circular pile optimizes the mass stored per unit area. However, restrictions due to available equipment, stacking methods, and ventilation may require alternative pile configurations and increase the necessary storage area. Furthermore, figures are representational and do not take into account necessary pile spacing for fire control. Spontaneous combustion is a concern when dealing with large piles of high moisture material which are required for an energy plant’s operation.

Conclusion

There is no single solution that will solve the U.S.’s future energy needs. Replacing the large amounts of fossil fuel based energy with renewable alternatives will require the use of numerous technologies, methods, and natural resources. Energy production methods should be best matched with a region’s available natural resources. The U.S. Corn Belt currently produces a large volume of unused corn cobs. If harvested, these cobs can supply many near-term uses in the renewable energy field. Energy crops such as switchgrass and miscanthus are not grown in large volume the U.S. and will require acceptance and development before their potential is fully realized. Corn cobs are a viable energy feedstock and hold much promise for use in local and regional energy production. Corn cobs together with other bioenergy feedstocks and renewable energies, will provide the energy to be less dependent on fossil fuels and to reduce their harmful effects.

Table 2. Cost of Nitrogen Replacement Associated with Corn Plant Removal

	Component	% of Total Plant	Plant Matter Harvested (lb/acre)	% Nitrogen of Plant Matter	Nitrogen Removed With Plant Matter (lb of N/acre)	Nitrogen Replacement Cost ($/ton of Plant Matter)	Nitrogen Replacement Cost ($/acre)
Grain Harvest	Grain	48	7680	1.44	111	17.36	66.67
Cob Harvest	Cobs	7.5	1210	0.33	4.0	3.97	2.40
Stover Harvest	Stalks	22	3550	0.43	15	5.08	9.01
	Leaves	10.6	1710	1.80	31	21.78	18.62
	Sheaths	5.3	855	0.64	5.5	7.73	3.30
	Husks	4.3	694	0.36	2.5	4.33	1.50
	Shanks	1.5	242	0.50	1.2	5.96	0.72
	Cobs	7.5	1210	0.33	4.0	3.97	2.40
	Tassels	0.5	81	0.97	0.8	11.86	0.48
	Lower Ears	0.5	81	2.04	1.6	23.73	0.96
	Silks	0.2	32	3.50	1.1	41.29	0.66
	Stover Harvest Totals	52.4	8455	NA	62.7	8.91*	37.66*

Source : Hanway, J.J. 2007

The information in this table is based on a 161 bu/acre corn yield. Costs in this table are based off of $985 / ton anhydrous ammonia (82-0-0) and application rates of anhydrous ammonia at: 135lb/acre for grain harvest; 4.9 lb/acre for cob harvest; and 76.5 lb/acre for stover harvest. *Although nitrogen replacement required from anhydrous ammonia is reduced by the application of diammonium phosphate, this table does not reflect this reduction. The reduction is taken into account in the summary of macro-nutrient replacement in table 4.

Table 3. Cost of Phosphorus Replacement Associated with Corn Plant Removal

	Component	**% of Total Plant**	**Plant Matter Harvested (lb/acre)**	**% P_2O_5 of Plant Matter**	**P_2O_5 Removed With Plant Matter (lb of P_2O_5/acre)**	**P_2O_5 Replacement Cost (\$/ton of Plant Matter)**	**P_2O_5 Replacement Cost (\$/acre)**
Grain Harvest	Grain	48	7680	0.69	53	14.78	56.74
Cob Harvest	Cobs	7.5	1210	0.11	1.3	2.30	1.39
Stover Harvest	Stalks	22	3550	0.14	5.0	3.02	5.35
	Leaves	10.6	1710	0.69	12.0	15.03	12.85
	Sheaths	5.3	855	0.37	3.2	8.01	3.43
	Husks	4.3	694	0.21	1.5	4.63	1.61
	Shanks	1.5	242	0.18	0.4	3.54	0.43
	Cobs	7.5	1210	0.11	1.3	2.30	1.39
	Tassels	0.5	81	0.5	0.4	10.57	0.43
	Lower Ears	0.5	81	0.87	0.7	18.51	0.75
	Silks	0.2	32	0.87	0.3	20.07	0.32
	Stover Harvest Totals	52.4	8455	NA	24.8	6.28*	26.55*

Source : Hanway, J.J. 2007

The information in this table is based on a 161 bu/acre corn yield. Costs in this table are based off of \$985 / ton diammonium phosphate (DAP) (18-46-0) and application rates of DAP at: 115 lb/acre for grain harvest; 2.8 lb/acre for cob harvest; and 54 lb/acre for stover harvest. *Although DAP contains nitrogen, the nitrogen value is disregarded in this table. The prices reflect the use of DAP for phosphorous replacement only. The nitrogen content of DAP is taken into account in the summary of macro-nutrient replacement in table 4.

Table 4. Cost of Potassium Replacement Associated with Corn Plant Removal

	Component	**% of Total Plant**	**Plant Matter Harvested (lb/acre)**	**% K_2O of Plant Matter**	**K_2O Removed With Plant Matter (lb of K_2O/acre)**	**K_2O Replacement Cost ($/ton of Plant Matter)**	**K_2O Replacement Cost ($/acre)**
Grain Harvest	Grain	48	7680	0.50	38.4	6.40	24.58
Cob Harvest	Cobs	7.5	1210	0.62	7.5	7.93	4.80
Stover Harvest	Stalks	22	3550	0.90	32	11.54	20.48
	Leaves	10.6	1710	2.05	35	26.20	22.40
	Sheaths	5.3	855	1.74	15	22.46	9.60
	Husks	4.3	694	1.32	9.2	16.97	5.89
	Shanks	1.5	242	1.68	4.1	21.69	2.62
	Cobs	7.5	1210	0.62	7.5	7.93	4.80
	Tassels	0.5	81	1.70	1.4	22.12	0.90
	Lower Ears	0.5	81	3.00	2.4	37.93	1.54
	Silks	0.2	32	2.57	0.8	32.00	0.51
	Stover Harvest Totals	52.4	8455	NA	107.4	16.26	68.74

Source : Hanway, J.J. 2007

The information in this table is based off a 161 bu/acre corn yield. Costs in this table are based off of $768 / ton potassium chloride (MOP) (0-0-60) applied at rates of: 64 lb/acre for grain harvest; 12.5 lb/acre for cob harvest; and 179 lb/acre for stover harvest.

Table 5. Summary of Macro-Nutrient Replacement Cost Associated with Corn Plant Removal

	Nitrogen Replacement Cost ($/acre)	**P_2O_5 Replacement Cost ($/acre)**	**K_2O Replacement Cost ($/acre)**	**Total Nutrient Replacement Cost ($/acre)**	**Total Nutrient Replacement Cost ($/ton)**
Grain Harvest	54.21*	56.74	24.58	135.53*	35.29*
Cob Harvest	2.10*	1.39	4.80	8.29*	13.70*
Stover Harvest	31.83*	26.55	68.74	127.12*	30.07*

Source : Hanway, J.J. 2007

Costs in this table are based off of: $985/ton anhydrous ammonia (82-0-0); $985/ton diammonium phosphate (DAP) (18-46-0; and $768 / ton potassium chloride (MOP) (0-0-60). *The value of nitrogen content of DAP to be applied is taken into these figures and reduces anhydrous ammonia application rates.

Table 6. Corn Cob Storage Area Requirements

Circular Pile

Cobs Stored (ton)	Storage Volume (ft³)	Angle of Repose	Radius of Pile (ft)	Diameter of Pile (ft)	Height of Pile (ft)	Area Covered (ft²)	Cobs Stored Per Area (lb/ft²)
9000	1058824	min	114.7	229.5	76.8	41356	435
		ave	111.6	223.3	81.1	39160	460
		max	108.7	217.4	85.5	37130	485

Windrow Pile

Width of Pile (ft)	Length of Pile (ft)	Angle of Repose	Height of Pile (ft)	Volume of Pile (ft³)	Cobs Stored (ton)	Area Covered (ft²)	Cobs Stored Per Area (lb/ft²)
60	1650	min	20.1	976899	8303.6	98227	169
		ave	21.8	1060225	9011.9	98227	183
		max	23.6	1148336	9760.9	98227	199

Corn Cob Angle of Repose (degree)	
min	33.8
average	36
max	38.2

Corn Cob Bulk Density (lb/ft³)	
17	
equals 272.3	(kg/m³)

Sources: Anderson, G.A., Bern, C.J. 1984; Bulk and Powder

This table shows the storage area required to store 9000 tons of corn cobs in a circular pile and windrow piles. This table uses a corn cob bulk density of 17 lb/ft3 and an average angle of repose of 36 degrees. For a graphical comparison of corn cob and corn stover storage area requirements see figure 1.

Representation of Storage Area for 9000 tons of Corn Cobs and Corn Stover

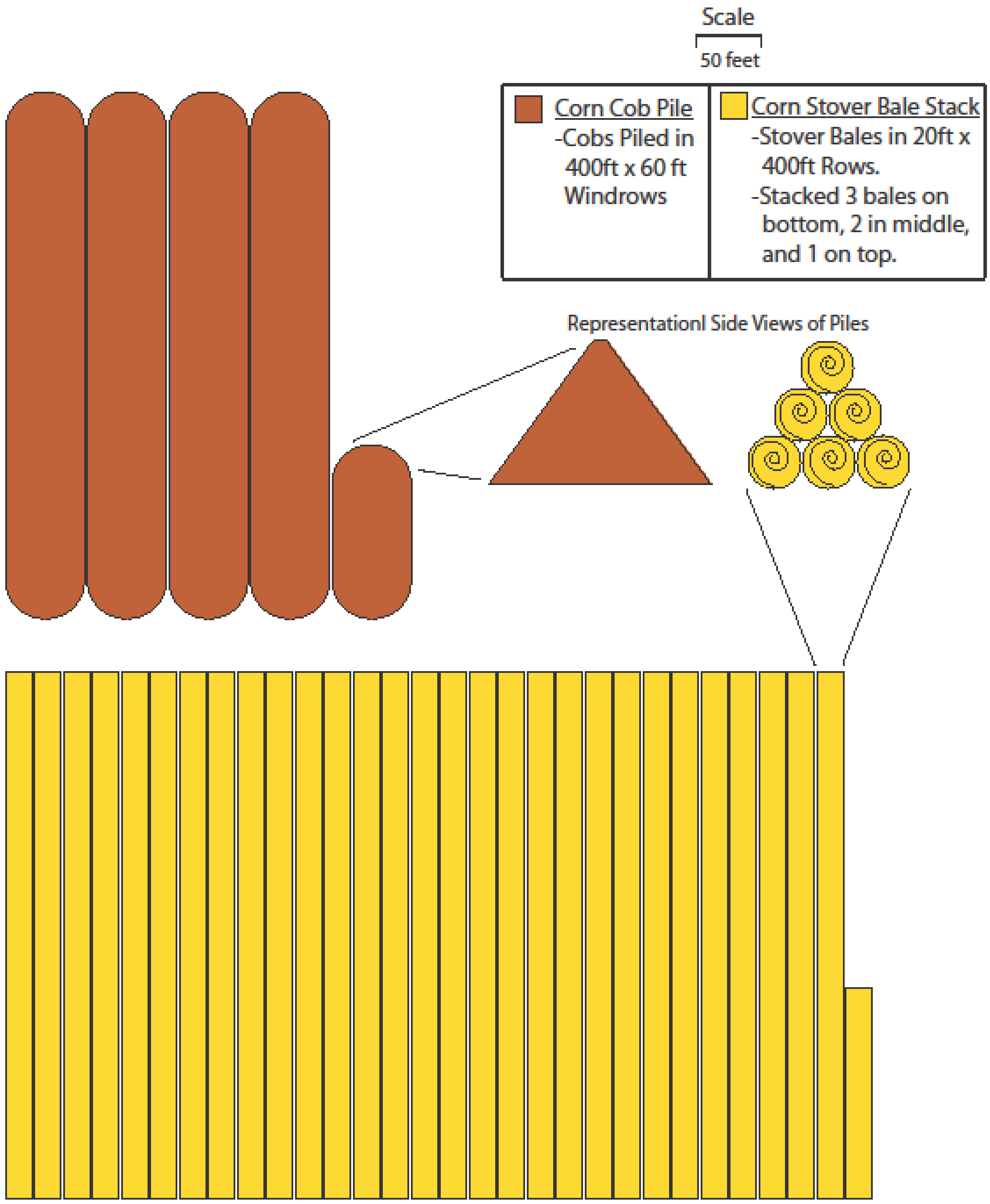

Figure 1. This figure represents the storage area necessary for 9000 tons of corn cobs and stover bales. The area representations are to scale.

Corn Cob Collection Attachments

Figure 2 Ceres Residue System™- Attachment sorts stover at back of combine and collects cobs in hopper on top of combine

Figure 3. Ceres Residue System™- Full cob hopper emptied into truck

Figure 4. Cob Caddy™- Self contained cob collection trailer. Cobs collected in wagon basket and stalks, leaves and husks are spread onto field.

Figure 5. Full Cob Caddy™ wagon side-dumped cobs into tender wagon.

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References

Anderson, G.A., Bern, C.J. 1984. Dynamic Angle of Repose of Corncobs Placed by Three Mechanical Means. Trans. ASAE. 1984. 935-936.

Bargiel, D.A., Liljedahl, J.B., Richey, C.B. 1982. A Combine Cob Saver. Trans. ASAE. (Oct. 1982): 544-548.

Clark, T.T. and Lathrop, E.C. 1953. Corncobs-Their Composition, Availability, Agricultural and Industrial Uses. USDA-ARS North Regional Research Lab., Peoria, IL. AIC-177

Dunning, J.W., Winter, P., Dallas, D. 1948. The Storage of Corncobs and Other Agricultural Residues for Industrial Uses. USDA-ARS, North Regional Research Laoratory, Peoria, IL. AIC-177.

EIA-DOE. International Energy Annual 2005. June-October 2007. http://www.eia.doe.gov/emeu/iea/contents.html

EIA-DOE. Annual Energy Review 2007. U.S. Primary Energy Consumption by Source and Sector. June 2008. Report No. DOE/EIA-0384(2007) http://www.eia.doe.gov/oiaf/ieo/index.html

EIA-DOE. International Energy Outlook 2008. http://www.eia.doe.gov/oiaf/ieo/index.html

Foley, K. 1978. Physical Properties, Chemical Properties and Uses of the Anderson's Corncob Products. The Andersons, Maumee, OH.

Fryrear, D.W., P.L. Sutherland, G. Davis, G. Hardee, and M. Dollar. 2001. Wind Erosion Estimates with RWEQ and WEQ. *In Proceedings of Conference Sustaining the Global Farm*, 10th International Soil Conservation Organization Meeting, May 24-29, 1999, Purdue University. Pp 760-765.

Graham, R.L., Nelson, R., Sheehan, J., Perlack, R.D., Wright, L.L. 2007. Current and Potential U.S. Corn Stover Supplies. Agron. J. 99 (2007) 1-11.

Gani,A., Naruse, I. 2007. Effect of cellulose and lignin content on pyrolysis and combustion characteristics for several types of biomass, Renewable EnergyVolume 32, Issue 4, , April 2007, Pages 649-661. http://www.sciencedirect.com/science/article/B6V4S-4JSFV9S2/2/014e178563e1fc2f02373c7a112b3bc8

Hanway, J.J. Iowa State University Research. Integrated Crop. 22(Aug 2007) 498. http://www.ipm.iastate.edu/ipm/icm/2007/8-6/nutrients.html

Linden, D.R., Clapp, C.E., Dowdy, R.H. 2000. Soil & Tillage Research 56 (2000) 167-174.

Nelson, R.G., Walsh, M. Sheehan, J.J, Graham, R.. 2004. Methodology for Estimating Removal Quantities of Agricultural Residues for Bioenergy and Bioproduct Use. Appl. Biochem. Biotechnol. 113:13-26.

Mclaughlin SB, Samson R, Bransby DI, Wiselogel A. Evaluating physical chemical and energetic properties of perennial grasses as biofuels. In: Bioenergy '96—The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies. Nashville, TN, USA, 1996.

Meyers, D.K., Underwood, J.F. Harvesting Corn Residue. Ohio State University Extension, Department of Horticulture and Crop Science. http://ohioline.osu.edu/agf-fact/0003.html

Perlack, R.D., Wright, L.L, Turhollow, A.F., Graham, R.L., Stokes, B.J., Erbach, D.C. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. 2005. U.S. DOE, USDA and Oak Ridge National Laboratory.

Powder and Bulk.Com. Engineering Resources - Bulk Density Chart. 16 June 2008. http://www.powderandbulk.com/resources/bulk_density/material_bulk_density_chart_c.htm

Riggins, J.K., Vaughn, D.H., Lambert, A.J. 1981. Corncobs Versus Corn Stalks: A Comparison of Energy Value for Drying Corn. Agricultural Energy. (2):280-285. ASAE Publ. 4-81.

Smith, R.D., Pert, R.M., Liljedahl, J.B., Barrett, J.B., Doering, 1985. Corncob Property Changes During Outside Storage. Trans. ASAE 28(3) (May-June 1985) 937-942, 948.

USDA-ERS. Data Sets-U.S. Fertilizer Use and Price-Table 7. Oct. 2007. http://www.ers.usda.gov/Data/FertilizerUse/

USDA-NASS. Quick Stats-Crops and Plants. 23 July 2008. http://www.nass.usda.gov/QuickStats/index2.jsp#top

Wilhelm, W.W., Johnson, J.M.F., Hatfield, J.L., Voorhees, W.B., Linden, D.R.. 2004. Crop and Soil Productivity Response to Corn Residue Removal: A Literature Review. Agronomy Journal. Agron. J. (96):1-17.