DEVELOPING A BIOMATERIALS INDUSTRY IN NORTH DAKOTA

Subaward No. FAR0018581

under NDSU Prime R-010-022

MBI Project No. 1655.001

FINAL REPORT

February 28, 2014

Submitted to
North Dakota Industrial Commission

Submitted by
North Dakota State University and MBI

Contacts:
Nancy Hodur, NDSU
701-231-7357
nancy.hodur@ndsu.edu
Department of Agribusiness and Applied Economics, NDSU
P.O. Box 7610
Fargo, ND 58108

Bernie Steele, MBI
517.336.4645
steele@mbi.org
3815 Technology Boulevard
Lansing, MI 48910-8121

NDSU NORTH DAKOTA STATE UNIVERSITY

mbi De-Risking and Scale-Up of Bio-Based Technologies

TABLE OF CONTENTS

List of Tables

Title **page**

List of Figures

Title **page**

1.0 Executive Summary

A major untapped resource is agricultural biomass, the non-edible crop residues such as stalks and leaves that remain after grains are harvested. This biomass constitutes half to two-thirds of the weight of crop material; therefore, about 2 billion to 3 billion tons of biomass are produced every year, of which some must be left in the field to maintain soil quality. Biomass is composed mostly of sugar polymers that are tightly bound and intertwined with an indigestible structural material, lignin. If these sugars could be readily accessed, the biomass could potentially be converted into animal feed and renewable fuels and chemicals.

There are several major challenges in capturing the value of agricultural biomass: 1) cost-effectively altering the biomass to an upgraded form in which the constituent sugars are easily accessible, 2) handling, storing and hauling low-density biomass from the field to the site of eventual use, and 3) establishing the upgraded biomass as a readily tradable commodity with clear economic value for the diverse players involved in its production, processing and use. MBI, in collaboration with Michigan State University, is developing an innovative technology (AFEX) and implementation concept that simultaneously addresses all three challenges, and thus has the potential to fully unlock the value of biomass.

AFEX™, our transformative biomass processing technology, addresses the first challenge by using ammonia to treat agricultural biomass at moderate pressures and temperatures. As a result, the biomass microstructure is altered, and the sugar polymers are partially unwound and loosened from the lignin, rendering the sugars more accessible. AFEX can increase sugar access substantially; while only 20% of the sugars are accessible in untreated biomass, the accessible sugar *quadruples* to nearly 80% as a result of AFEX treatment. Another unique feature of AFEX is that the treated biomass can be easily and economically pelletized to increase its bulk density by a factor of 10, resulting in grain-like handling characteristics and improved transportation economics.

A biomass processing depot concept has been proposed as one way to reduce costs and overcome many of the logistic challenges of the lignocellulosic biomass feedstock supply chain (Hess et al., 2009; Hess et al., 2009b; Eranki et al., 2011). In this concept, raw biomass harvested from farmlands is transported relatively short distances to small-scale depots for processing into denser and more uniform stable commodities. Those commodity feedstocks can then be stored economically and transported readily over longer distances to large-scale biorefineries for conversion into biofuels and bio-based chemicals. Methods for pretreatment of biomass at depots may include mechanical treatments such as size reduction or pelletization, as well as chemical treatments (Thompson et al., 2013).

AFEX is one method that could be used for chemical pretreatment of biomass at regional depots. AFEX treatment involves contacting biomass at moisture levels from 20 to 80 wt% with ammonia liquid or vapor in a pressure vessel to achieve ammonia:biomass weight ratio of 0.2–4 at temperatures from 40 to 120°C and pressures from 2 to 40 atm for treatment times ranging from 10 to 60 min, followed by release of ammonia vapor from the vessel, residual ammonia removal from the biomass by drying or steam stripping and recovery of the treated biomass. AFEX does not significantly hydrolyze hemicellulose to soluble sugars or oligomers, does not generate any liquid side streams and does not significantly alter the composition of the biomass. AFEX has been shown to be a highly effective pretreatment for corn stover (Teymouri et al., 2005), and a wide range of other agricultural residues and energy crops, including *Miscanthus*, switchgrass and wheat straw (Murnen et al., 2007; Alizadeh et al., 2005; Bals et al., 2010). AFEX treatment has also been shown to mobilize lignin to act as a natural binder, facilitating densification of biomass (Dale et al., 2011).

We envision that AFEX technology will be implemented at local “depots,” which will receive the raw biomass from farms located within a 5-10 mile radius. This eliminates the cost of creating expensive transportation networks for low-density raw materials. The AFEX pellets, which have a long shelf life and 8 times greater density than raw biomass, can be economically stored and shipped from depots to markets using existing grain infrastructure, addressing the second challenge.

The technology was originated by Professor Bruce Dale at Michigan State University, who has been researching the science underpinning AFEX for over two decades. In 2010, MBI made a significant design breakthrough, resulting in a novel reactor with reduced capital and operating cost. In 2011, MBI won a $4.3M U.S. Department of Energy award to scale up the technology from laboratory prototype (10 liter) to pilot scale (2 X 450 liter; Figure 20). In 2013, MBI commissioned the pilot AFEX reactor and initiated shakedown operations. The pilot reactor is being used to refine the technology and support small-scale animal feed trials and biorefinery applications development.

One of the key innovations in the new AFEX-3 design is that ammonia recovery and recycle is inherent in the operation. Recovery of ammonia as substantially dry vapor, suitable for recompression from vertical packed beds significantly simplifies the AFEX process compared with conventional AFEX designs. Direct recompression of the dry vapor stripped from a lead bed, coupled with the absorption of that compressed vapor on a lag bed, eliminates the need for an ammonia recovery dryer or column, or arrangements of ammonia flash and quench tanks, as required in conventional designs described in the literature (Sendich et al., 2008; Laser et al., 2009; Holtzapple et al., 1992). This reduction in equipment requirements yields significant reduction in the capital cost of the system, particularly at the smaller scales anticipated for biomass processing depots. Our preliminary analysis of a depot processing 100 tons of corn stover per day shows that greater than 50% reduction in capital cost can be realized using a packed bed system in place of a conventional AFEX design. During the packed bed AFEX cycle, the compressor operates only intermittently, during bed-to-bed ammonia transfer and, consequently, the cost associated with the compressor electrical load is not a significant component of the overall treatment cost.

The AFEX pellets can be used both as a feed for ruminant animals or as a feedstock for sugar-based fermentations to produce industrially important fuels and chemicals. Testing during this project has validated the efficacy in both applications.

Biomass production and total recoverable biomass from wheat straw and corn stover were estimated by crop reporting district and for the state using the Harvest Index Formula. Biomass production is a function of yields and using historic wheat and corn grain yields biomass production was estimated. Recoverable biomass was calculated using published biomass recovery rates using widely accepted methods and equipment for gathering, loading and transporting biomass. Sufficient quantities of recoverable biomass are available in every region of the state to support multiple AFEX pre-treatment depots. Based on an Olympic average of the last five years production of wheat and corn, the theoretical maximum number of 110 tons per day pretreatment deports that could be supplied with biomass in North Dakota is 195. While the theoretical maximum is not likely achievable, it does provide some to the quantity of available biomass in the state.

Biomass feedstock cost was estimated using feedstock soil nutrient value, custom harvesting rates for gathering, baling, and transportion and a producer incentive. Nutrient values were calculated on both a per ton and per acre basis. While biomass will likely be bought and sold on a per ton basis, a per acre valuation will enable producers to evaluate the potential value of biomass in terms that are compatible with operating budgets. Cost per ton of wheat straw was estimated to be $57.66 per ton or $46.87 per acre delivered to the AFEX pre-treatment depot. Cost per ton of corn stover was estimated to be $68.10 per ton for corn stover and $66.30 per acre delivered to the pre-treatment facility. More corn stover is produced per acre which accounts for some of the difference in cost per acre. Gathering corn stover also requires mowing and raking operations which also adds to the cost of collection.

One likely initial market for AFEX pre-treated biomass is ruminant livestock feed. Preliminary feeding trials suggest pre-treated biomass can be substituted for corn and achieve equivalent weight gain and carcass quality. While the assessment of available biomass suggests ample biomass to support multiple AFEX pre-treatment facilities, development and commercialization will likely be driven by demand. North Dakota ranks 10th in nation for total beef cow numbers, however most the state's beef industry is characterized by cow calf operations. While most of the calves produced in North Dakota are fed to finished weights in other states, livestock producers do background cattle in place (on ranch) and there are backgrounding and finishing lots in North Dakota. An assessment of the number of cattle fed in feedlots with a capacity of 500 head or more would suggest the current fed cattle livestock industry in North Dakota could support ten 110-tons per day AFEX pretreatment facilities. The assessment did not include an assessment of the market potential for cattle backgrounded in place. Analysis of findings from preliminary feeding trials is still on going. Additional research examining nutritional value and relative cost is needed to more thoroughly assess market potential in North Dakota.

Three regional economic impact scenarios were examined: a 110-tons per day depot, a 220-tons per day depot and a ten 110-tons per day depot system. The ten depot system was based on the estimate of the potential market for AFEX pretreated biomass in the state's cattle feeding industry. The economic contribution for both construction and operations was estimated. An economic contribution assessment measures the economic effects from in-state expenditures related to depot construction and operations.

A single 110-tons per day depot has a capital cost of $9.7 million, a 220-tons per day depot a capital cost of $18.4 million and a ten depot system a capital cost of $97 million. The one time economic contribution from construction activities was estimated to be $3.8 million, $7.3 million and $38.3 million for a 110 tons per day, a 220 tons per day and a ten 110 tons per day depot system, respectively. Capital costs were dominated by expenditures for specialized equipment that will likely be purchased from out of state vendors. In-state construction expenditures were largest in the construction and retail sectors with $1.7 and $1 million in expenditures, respectively. Economic effects of a single plant would likely accrue during a construction period of one year or less. Construction impacts from a 10 depot system would likely accrue over a multi-year period. State-wide total economic effects associated with construction activities were estimated to be $9.7 million, $18.2 million and $97.2 million for a 110-ton per day depot, a 220-tons per day depot and a ten 110-tons per day depot system, respectively.

The direct economic contribution from depot operations is annual and ongoing as long as the depot remains in operation. Direct economic impacts represent payments to North Dakota entities. Unlike construction effects, nearly all of the operations expenditures accrue to North Dakota entities. Expenditures for most inputs for production; wheat straw, corn stover, natural gas, ammonia, electricity, water and labor are all available for purchase from in-state entities and were allocated to the appropriate sector. Total direct expenditures related to operations were estimated to be $4.8 million, $8.9 million and $48 million for a 110-tons per day, 220-tons per day and a ten 110-tons depot system, respectively. Direct effects were greatest in Business and Personal Services which reflects payments for biomass collection and transportation. Payments to the Households sector reflect payment to farmers for biomass. A 110-tons per day depot would employ 16 full time equivalent workers while the 220-tons per day depot is more labor efficient and would employ 20 full time equivalent workers. A ten 110 tons per day depot system would employ 160 full time workers. Total operational impacts (direct and secondary) were estimated to be $13.3 million, $24.2 million and $133 million annually for a 110-tons per day, 220-tons per day and ten 110-tons per day depot system, respectively. The largest impacts would accrue to the Household and Retail Sectors.

While the economic effects are small relative to other major industries in North Dakota, AFEX pretreatment depots would be creating new economic activity using biomass that is largely underutilized. Further even though at this time the North Dakota state economy is very robust, economic conditions vary regionally. While some regions are growing rapidly other regions in the state are less robust. A system of AFEX pretreatment depots would likely be developed near livestock feeding operations which are concentrated in the southern tier and southwestern North Dakota. Those region’s economies are still heavily dependent on agriculture and economic diversification and development is a priority.

2.0 Introduction

There are several major challenges in capturing the value of agricultural biomass:

1) cost-effectively altering the biomass to an upgraded form in which the constituent sugars are easily accessible,
2) handling, storing and hauling low-density biomass from the field to the site of eventual use, and
3) establishing the upgraded biomass as a readily tradable commodity with clear economic value for the diverse players involved in its production, processing and use

MBI, in collaboration with Michigan State University, is developing an innovative technology (AFEX™) and implementation concept that simultaneously addresses all three challenges, and thus has the potential to fully unlock the value of biomass.

We have developed a novel design for pretreatment of biomass using ammonia as a catalyst. This treatment process has been demonstrated at bench scale (50 gram) and is called AFEX-3. It is anticipated to have much lower capital and operating costs over previous AFEX treatment processes. This process captures the ammonia on a "packed bed" of biomass thereby avoiding the need for ammonia recovery and storage required in previous AFEX systems.

3.0 Objectives

The goal of this project is to complete efforts to design a pilot scale plant for conversion of wheat straw and corn stover to various biomaterials (i.e. fuels, chemicals, animal feed, etc.). Specific objectives include:

1. Completion of a technology and process design that can meet commercial viability criteria as determined by techno-economic analysis;
2. Fabrication and validation testing of a prototype processing reactor system
3. Assessment of the rural development impact of such a technology

Final Report Deliverables include:

1. Design and build of a three packed bed reactor AFEX laboratory system that operates at 4.5 kg per cycle;
2. Prototype testing of a new AFEX reactor design that is less capital intensive;
3. Operate the reactor system to collect mass and energy balances necessary to design a pilot plant for the process;
4. Use the AFEX reactor to generate sufficient quantities of AFEX-treated material for applications testing of fermentation products systems and initial animal feeding trials;

5. Prototype testing of the system for continuous ammonia reuse;
6. Develop a pilot scale plan including a) process flow diagram; b) proforma of anticipated capital and operating costs; and c) plan for product development;
7. Develop a proforma for a regional biomass processing centers using the AFEX-3 reactor and determine rural development implications for the project. This will include updating the commercial business plan to address: a) deployment on a regional basis; b) more flexible by product potential; c) updating the techno-economic analysis with a focus on regional biomass processing and rural development; and d) updating the economic requirements for construction of a pilot scale plant.

4.0 Project Deliverables

Project deliverables are detailed in the follow section.

4.1 Design and Fabrication of a Three Reactor AFEX-3 Laboratory Scale Prototype

Design of a 10 kg per day AFEX-3 test skid capable of treating wheat straw and corn stover was completed and a prototype was fabricated (see additional details on prototype operational design in Deliverable 2 below). The system design is a three-bed configuration, with NH_3 transport from bed to bed. A design schematic of the prototype system (Figure 1) is shown below. Figure 2 is a drawing of a bed tube, and Figure 3 shows the fabricated test skid. Features of the design include:

- Bed tubes (Figure 2) are 4-inch OD stainless steel tube, 0.085-inch wall thickness. The length of the packed section of each tube will be approximately 48-inches, making the bed volume 553 in^3 (9.1 liter). Each tube has a 40-mesh stainless steel screen at the bottom to support the bed.

- Once packed, biomass beds may be pre-steamed, or NH_3 may be steam stripped, at atmospheric pressure by application of dry steam through the 2-inch ball valves.

- Four-way inlet (HV-104, -204, -304) and exit (HV-105, -205, -305) valves on each bed will allow for initial NH_3 vapor charge to bed 1, followed by elution of NH_3 from bed 1 to bed 2, from bed 2 to bed 3, and from bed 3 to bed 1, with an appropriate soak period to AFEX-treat the biomass in each bed. Pressure of NH_3 vapor eluted from each lead bed can be staged up using compressor P-015 before absorption on the lag bed.

- Makeup NH_3 can be vaporized in the inner tube of a tube-in-tube heat exchanger HX-008, with steam heat to the outer tube. The makeup NH_3 vapor can be compressed and charged to any bed through the compressor discharge manifold.

- Instrumentation includes:

  - Surface RTDs to monitor temperatures at the inlet (TE-102, -202 -302) and exit (TE-103, -203, -303) ends of each bed tube, as well as an in-line gage to monitor compressor discharge (TE-011) temperature.
  - Pressure gages to monitor head pressure (PI-101, -201, -301) of each bed, as well as compressor discharge (PI-012) pressure.
  - Batchtrol with Coriolis meter on the existing NH_3 pump skid to determine NH_3 charge and makeup mass.

- Safety features include a separate burst disk (PSE-106, -206, -306) on each bed, and pressure relief valve (PSV-005) on the compressor discharge manifold, to prevent over-pressurization of any part of the system. The existing NH_3 pump skid includes controls and pressure relief valves to prevent pump dead-heading or over-pressurization of HX-008 or delivery lines. The entire test skid will fit within existing ventilation areas in the MBI facility to contain any vapor releases.

The fabricated test skid is shown in Figure 3.

Design calculations – Based on mass and energy balance calculations for the AFEX 3 test skid, equipment specifications include:

- Compressor (P-015) – GEA Bock (http://www.bock.de/en/home.html) model F2 NH3, 2-cylinder reciprocating type, displacement 10.5 m^3/hr (6.2 scfm) at 1,450 rpm, maximum discharge pressure 25 bar (348 psig). This is apparently the smallest compressor for NH_3 service available.

- NH3 Vaporizer (HX-008)- Exergy (http://exergyllc.com/) model 00413, 316 stainless steel tube-in-tube heat exchanger, heat transfer area 0.11 m^2 (1.2 ft^2), maximum inner tube pressure 3,200 psig at 400^{o}C, maximum outer tube pressure 1,200 psig at 400^{o}C. With low pressure (15 psig) steam condensing on the outer tube, this exchanger should be capable of safely vaporizing up to 150 g/min of liquid anhydrous NH_3, which will be delivered from the NH_3 pump skid.

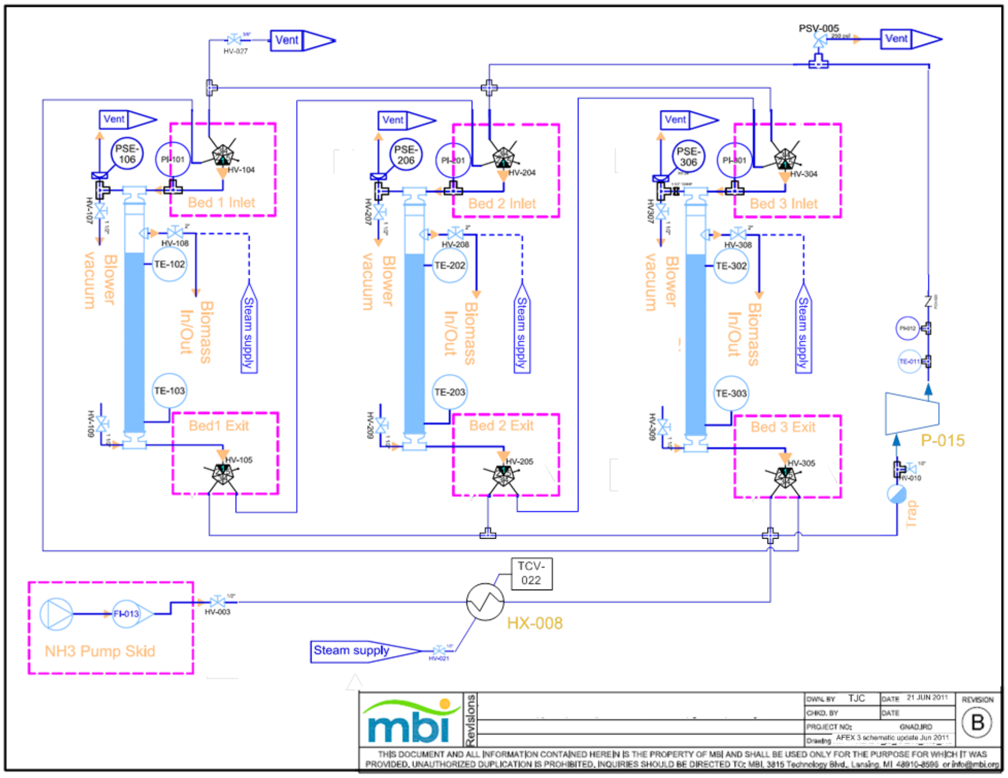


Figure 1. Design schematic of AFEX-3 prototype

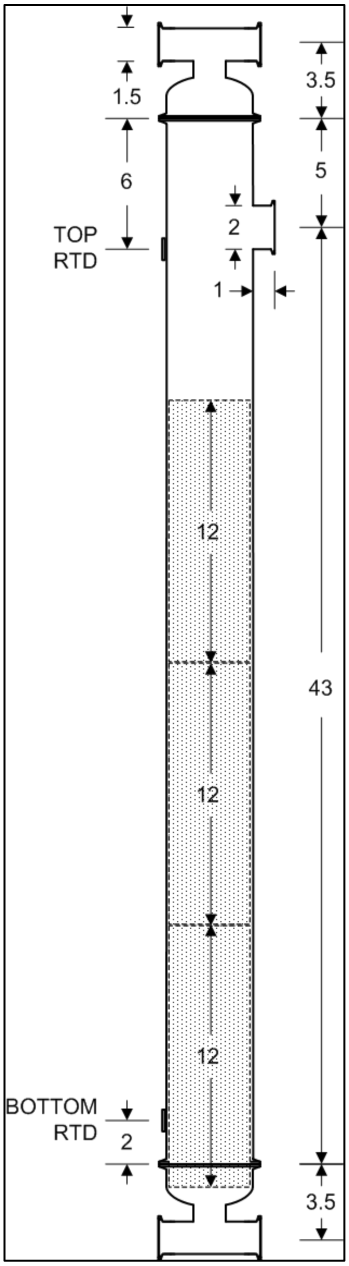


Figure 2. Drawing of a bed tube showing dimensions in inches, with locations of ports and positions of RTDs used for temperature measurement. Shaded rectangles indicate the positions of the three baskets containing the biomass bed (Campbell et al., 2013)

Figure 3. Photo of the packed bed AFEX-3 reactor system. (Campbell et al., 2013)

The design basis for the test skid bed tubes is approximately 1.5 kg of biomass per bed, and about 10 kg of treated biomass per day. The bed tube volume will be fixed at about 9.1 liter per bed, as described above. Consequently, the actual amount of biomass treated in each bed will depend on the bed density. Recently published data (Chevanan et. al, 2010) provides relationships between particle size and bed density for various biomass types, which allows us to calculate the expected bed masses for the AFEX 3 skid. The calculation results are shown in Figure 4. The dry mass of treated biomass may be as high as 1.2 kg/bed for fine ground switchgrass, or as low as 0.3 kg/bed for coarse wheat straw. Output of AFEX-treated biomass (kg/day) from the test skid will depend on both the bed mass (kg/bed), and the number of bed cycles that can be completed per day. For wheat straw at 4 mm particle length, for example, we can expect about 0.5 kg/bed, so completion of 20 bed cycles per day will generate 10 kg/day of AFEX-treated wheat straw.

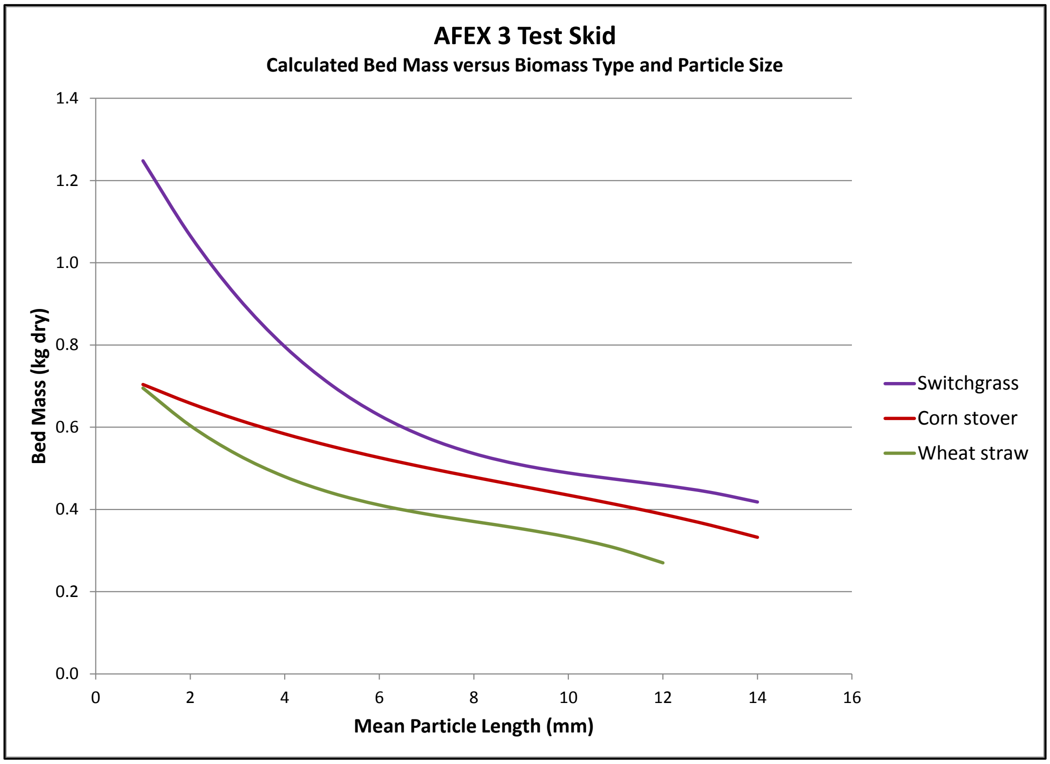


Figure 4. Expected bed masses for AFEX-3 prototype

4.2 Operate the Reactor System to Collect Mass and Energy Balances Necessary to Design a Pilot Plant for the Process

The effects of a cyclic batch process using presteaming followed by absorption of compressed ammonia vapor, then release of bed pressure and direct steam stripping to remove residual ammonia, on packed beds of corn stover and wheat straw, were investigated in the prototype system to establish the technical feasibility of the AFEX-3 method,. The effectiveness of this packed bed AFEX treatment for enhancing enzyme hydrolysis sugar yields and facilitating pellet formation were measured.

4.2.1 Experimental

Corn stover, wheat straw sources & size reduction

Conventional multipass, low-cob corn stover was harvested and baled by Iowa State University (IA, USA) on 23 October 2011. The stover was sourced from a field located at the GPS coordinates (42.213953, -93.742377). Following grain harvest, the stover was windrowed using a Hiniker 5600 Series side discharge windrowing stalk chopper (MN, USA), and baled using a Massey Ferguson MF2170XD large square baler (Kenilworth, UK). The average bale weight was 420 kg. The bales were stored under tarps until milled for use. This material was then milled to pass through a 1 inch screen using a Vermeer BG 480 grinder prior to drying to less than 5% moisture. Mini bales of wheat straw labeled as Rhino EZ-Straw® (MI, USA) (weighing approximately 18 kg, with 5% moisture) were purchased from a local farm (Webberville, MI, USA). The wheat straw was ground to pass through a 1.2-inch screen using a Wiley® mill (Thomas Scientific, NJ, USA).

The composition of corn stover and wheat straw was analyzed using the laboratory analytical procedures developed by the National Renewable Energy Laboratory (CO, USA) and the data are presented in **Table 1 (Sluiter et al., 2010)**.

Table 1. Ash and carbohydrate composition of corn stover and wheat straw (based on dry weight)*

Biomass	**Glucan (%)**	**Xylan (%)**	**Arabinan (%)**	**Galactan (%)**	**Mannan (%)**	**Ash (%)**
Corn Stover	34.7	18.9	2.9	1.6	0.53	5.9
Wheat Straw	38.3	20.2	1.2	2.4	0.4	4.1

* All experiments were performed in duplicate and the reported results are the average of the duplicate runs

Ground biomass at moisture content of approximately 5 wt% (total weight basis) was moistened to 25 wt% by spraying with deionized water, then packed into stainless steel baskets at bed density of 100 kg (dry) per m^3. A photo of a basket packed with corn stover is shown in the Figure 3 inset; three 12-inch long baskets were inserted into each reactor tube (Figure 2). Packing loose biomass into baskets for insertion into the bed tubes offered two advantages over simply dumping loose biomass in and out of the bed tubes. First, the use of baskets simplified transport of the treated biomass out of the reactor tubes. AFEX treatment mobilizes the lignin in raw biomass and the mobilized lignin acts as a natural binder, causing the fibers to stick together. The flowability of the treated biomass was inadequate to allow it to be dumped easily out of the bed tubes. The baskets, however, could be easily removed from the bed tubes, and then the treated biomass was readily removed from the baskets by flexing the mesh shell. The second advantage was the ability to control the compression of the biomass as it was packed into baskets. Packed bed AFEX requires bed porosity greater than 85 vol% to facilitate steam and ammonia vapor transport through the bed. Loose corn stover at an average 1-inch particle size typically has a bulk density of only 50 kg/m3, while wheat straw loose bulk density is only 51 kg/m^3 (Mani et al., 2004). Both corn stover and wheat straw at 1-inch particle size can be compressed to 100 kg/m^3 bed density, allowing more biomass to be treated per bed cycle, without reducing the bed porosity below 85 vol%. The basket shells were fabricated by spot welding stainless mesh with 40 openings per inch (McMaster-Carr, Atlanta, GA, USA) into a cylindrical sleeve approximately 3.75 inches in diameter and 12 inches long, then welding the sleeve to a disc of 22 gauge perforated stainless steel sheet with 0.0625- inch diameter round holes, 41% open area (McMaster- Carr). A 0.25-inch diameter stainless steel threaded rod attached to the perforated sheet disc ran through the axis of the basket and was used to attach a second perforated sheet disk to the opposite end of the basket, forming a lid to hold the biomass in place. The basket shells fit closely to the inner diameters of the bed tubes, but were able to slide easily in and out of the tubes.

Prototype AFEX system

The packed bed AFEX reactor system was assembled on a portable skid, which supported three bed tubes (Figure 3). Dimensions and ports of the three bed tubes are shown Figure 2. In normal operation, the bed tubes were mounted vertically, with the inlet at the top and exit at the bottom; however, to investigate buoyancy effects during steam stripping, a bed of corn stover was treated with the bed tube mounted horizontally. Each individual bed tube was fabricated from 4-inch outer diameter stainless steel tube, wall thickness 0.085 inch, with sanitary ferrules welded to the tube at either end; overall length was 48 inches. Each bed tube had a 2-inch diameter side port located 5 inches from the top. At the top and bottom of each bed tube, a reducing 'bell' tee was connected by an EPDM rubber gasket, using a high-pressure bolted sanitary clamp. Each bell tee had two 1.5-inch diameter ports for connection to inlet and exit multiport valves, as well as vent valves. The three baskets containing the packed biomass were inserted into the bed tubes by removing the top bell tee. The top bell tee of each bed tube was fitted with a 1.5-inch diameter 300-psig rupture disk (Fike Corp., Blue Springs, MO, USA). Each bed tube and bell tee was insulated with a 1/16-inch thick coating of Temp-Coat 101 ceramic insulating coating (Temp-Coat® Brand Products LLC, LA, USA). Despite the coating of insulation, heat loss from the bed tubes to the surrounding air was substantial during the high-temperature steps of the AFEX treatment cycle. Bed tube temperatures were monitored using two surface-mounted resistance temperature detector elements (Omega Engineering, Inc., Stamford, CT, USA) adhered to the bare steel of the outer tube wall, one located 6 inches from the top and one 2 inches from the bottom of the tube. Bed tube inlet and exit ports were connected to multiport valves by 0.5-inch inner diameter flexible braided hose with compression fittings. Bed pressure was measured using a 0–250 psi gauge connected by means of a gauge tee to each bed inlet hose.

A schematic diagram showing the interconnection of the three bed tubes with the other system components is shown in Figure 1. Anhydrous liquid ammonia (Tanner Industries Ltd, Philadelphia, PA, USA) for initial and makeup charging was delivered from a storage cylinder by means of a diaphragm pump (Lewa, Inc., Holliston, MA, USA) at a rate of 80–100 g per min. The liquid ammonia was vaporized at approximately atmospheric pressure in the inner tube of a 0.11 m^2 tube-in-tube heat exchanger (Exergy LLC, Garden City, NY, USA) with saturated steam at less than 15 psig condensing in the outer tube. Fresh ammonia vapor from the heat exchanger or vapor released from the treated biomass beds was compressed in a two-cylinder single-stage ammonia compressor with 10.5 m^3 per h displacement (GEA Bock GmbH, Frickenhausen, Germany). Vapor recovered from the biomass beds was dried on the suction side of the compressor by passing through the 5-inch diameter shell of a 1.5 m^2 stainless steel shell-and-tube heat exchanger (ITT Standard, Buffalo, NY, USA) with industrial cold water passing through the 3/8-inch tubes. Condensate exiting the heat exchanger was collected in a 1-l trap vessel. The compressor discharge manifold was connected to a 0.5-inch 250 psig relief valve (Leser LLC, Charlotte, NC, USA), with the relief port connected to vent.

Biomass treatment sequence

Baskets containing ground biomass were assembled into the reactor tubes and AFEX-treated using a cycle of five steps: presteam, ammonia charge, soak, depressurize and steam strip. For treatment of several beds in series, the ammonia charge, depressurize and steam strip steps involved transfer of ammonia vapor from a lead bed to a lag bed, and the lag bed presteaming step was timed to end just as the soak period of the lead bed was ending, so that depressurization and steam stripping of the lead bed coincided with ammonia charging to the lag bed. To minimize operator exposure to ammonia vapor, the packed bed AFEX skid was operated within a curtained ventilation area with adequate air volume turnover to rapidly dilute any fugitive vapors to below exposure limits. Detailed descriptions of the operating sequence steps are:

1) ***Presteam*** – presteaming served to both preheat the biomass beds and displace entrained air. The biomass beds were presteamed by admitting steam at a rate of approximately 60 g per min to the top of the bed tube using a steam nozzle attached to the 2-inch diameter side port. During presteaming steam pressure at the top of the bed was less than 3 psig, and the bottom vent port valve of the tube was left open to the atmosphere to allow displaced air to escape from the bed. Less than 30 s after introducing steam to the bed, the bed tube top temperature reading increased to more than 80°C. Presteaming continued until the bottom temperature reached within 5°C of the top temperature, at which point steam flow was stopped and the bottom vent port valve was closed;

2) ***Ammonia charge*** – following immediately after presteaming, the bed was charged with compressed ammonia to a load of 1 kg ammonia per kg dry biomass. Compressed vapor was charged to the biomass bed until a pressure of 200 psig was reached. The bed was then allowed to soak until the pressure had dropped below 160 psig, and then charged with compressed vapor back to 200 psig. This procedure was repeated until the target ammonia mass loading of 1 kg per kg of dry biomass was achieved. For initial or makeup charging, the vapor sent to the compressor suction was fresh ammonia from the evaporator, while for treatment of several beds in series, the vapor source was from the previous bed pressure release and steam stripping;

3) ***Soak*** – following ammonia charging, beds were allowed to soak for 30 min. During the soak period, the bed pressure typically dropped below 110 psig, due both to ammonia vapor permeation into the moist biomass and heat loss from the bed to the surrounding air;

4) ***Depressurize*** – at the end of the soak period, the bed exit valve was slowly opened to release vapor from the bed. The vapor released from bed depressurization was sent to the presteamed lag bed, until the two bed pressures were equal, at which point the lead bed was pulled down to atmospheric pressure using the compressor suction, with the compressed vapor sent to the lag bed. Alternatively, if the bed being treated was the last in the series, the vapor from depressurization was simply vented until the bed reached atmospheric pressure;

5) ***Steam strip*** – approximately one half of the ammonia charge remained on the bed after depressurization. This residual ammonia was removed from the bed by direct steam stripping. As in presteaming, steam was admitted to the top of the bed at a rate

of approximately 60 g per min using a steam nozzle attached to the 2-inch diameter side port. The vapor driven off of the bottom of the bed was sent through the condenser and trap to the compressor suction, and the compressed vapor sent to the next bed in series. Steam stripping was stopped intermittently to allow the lag bed pressure to drop from 200 psig to below 160 psig. Steam stripping was stopped when the bed tube bottom temperature had climbed to within 10°C of the top temperature, which was typically greater than 80°C.

Following bed-to-bed ammonia transfer, makeup ammonia was added to the lag bed as part of its ammonia charging step, to compensate for residual ammonia not removed from the lead bed, and for ammonia lost as condensate collected in the compressor suction trap. Based on the measured ammonia mass balance and measurements of the condensate volume (data not shown), it was calculated that 2% of the ammonia charge was not removed by steam stripping, and that 8% of the ammonia charge was recovered as condensate; therefore, 10% makeup ammonia was added to each bed in series after the initial bed. Note that while the 2% ammonia not removed by steam stripping represents ammonia bound to the biomass, the 8% in the condensate is recoverable by purging, although that was not done in these experiments. The 2% of the ammonia charge bound to the biomass is available as a nitrogen source for subsequent downstream fermentation of sugars liberated from the biomass by enzyme hydrolysis.

Ammonia recovery procedure

A set of experiments were conducted to measure the quantity and composition of ammonia vapor removed from beds of corn stover and wheat straw during steam stripping. In these experiments, beds of biomass were treated as described in steps 1–4 above. The beds were presteamed, charged with fresh ammonia (not ammonia recovered from another bed) then allowed to soak for 30 min, and then the pressure released to vent. A resistance temperature detector probe (Wahl Instruments, Inc., Culver City, CA, USA) was then inserted into the bottom bell tee of the tube, with the sensing element located less than 4 inches from the bottom of the lowest basket in the bed. A flexible hose was connected to the bottom bell tee, with the other end of the hose immersed in a 1-l portion of 0.5 molar citric acid. As steam stripping proceeded as described above, the vapor exiting the bed was trapped in the citric acid for 1 min, then the hose was switched to a second portion of 0.5 molar citric acid and the temperature of the vapor was recorded. In this way, 1-min fractions of stripped vapor were trapped in citric acid. When the steam stripping was complete, the pH of the fractions were measured using a standardized probe, and the ammonia mass content of each fraction determined by comparing the pH to an ammonia/citric acid titration curve. The composition of the ammonia–water vapor mixture was determined from the temperature recorded for each fraction by interpolating from a table of saturated ammonia–water vapor properties (Tillner-Roth and Friend, 1998).

Ammonia recycle

In order to be economical, nearly all non-reacted ammonia must be transferred from bed to bed. It should be possible to replace any NH_3 lost to irreversible interaction with the biomass by the addition of makeup NH_3 vapor during the recompression and transfer of vapor from bed to bed. Steam was used as the ammonia stripping gas as described above. While three beds were initially designed for the laboratory scale reactor, the steam process can be designed to effectively recycle ammonia with only two beds.

Immediately after steam stripping, samples of biomass were taken to determine moisture and ammonia content analysis. Moisture was measured by moisture analyzer. The residual ammonia was measured by titration of the sample with a known amount of citric acid with a known pH as described above. An ammonia and citric acid titration curve was generated to calculate the amount of ammonia left in the biomass. Ammonia recovery was calculated based on wt% of the ammonia left in the biomass compared to the amount of ammonia charged to the bed. Based on the ammonia recovery, the required amount of make-up ammonia was added to the subsequent beds.

AFEX treatment in batch stirred reactor

To provide a performance benchmark, corn stover and wheat straw were treated in a 1-gallon pressure reactor as described previously (Hanchar et al., 2007). The process conditions were 60% moisture, reaction time of 30 min, temperature at 90°C and ammonia loading at 1 g of ammonia per g dry biomass. Temperature and concentration gradients were minimized in this small agitated vessel so that the biomass charge was uniformly treated under the AFEX conditions, providing a useful benchmark for comparison to the packed bed AFEX reactors.

Enzyme hydrolysis procedure

The performance of the packed bed AFEX process in treatment of corn stover and wheat straw was evaluated via enzyme hydrolysis. The enzymatic digestibility of AFEX-treated biomass was determined via enzymatic hydrolysis at low solid loading (Murnen et al., 2007). The hydrolysis test was carried out in Erlenmeyer flasks and the conditions were 50°C, pH 4.8 (0.05 M sodium citrate buffer), 3% solid loading (equivalent to 1% glucan loading) and agitated at 150 rpm in a constant temperature incubator shaker for 72 h. Combination of cellulase (Cellic Ctec2, provided by Novozymes), hemicellulase (Cellic Htec2, provided by Novozymes) and Multifect Pectinase (provided by Genencor®) was used in the enzymatic digestibility tests. Samples of all enzymes were sent to ServiTech laboratory (Hastings, NE, USA) for crude protein analysis (based on total nitrogen).

One of the unique features of the AFEX process is that the cellulose, hemicellulose and lignin present in the biomass are preserved and the composition of the biomass before and after the treatment is essentially the same. Therefore, composition of the untreated samples was used in enzymatic digestibility calculations. The required amount of enzyme was calculated based on 30 mg of enzyme protein (Ctec2 plus Htec2 plus pectinase) per gram of glucan. The enzyme cocktail containing 30 mg protein enzyme per gram of glucan consisted of 70% Ctec2, 15% Htec2 and 15% pectinase. In each set of experiments, appropriate controls were run to account for the amount of sugars that came with the enzyme cocktails. Hydrolysis yields of glucose and xylose were determined via high-performance liquid chromatography using a Bio-

Rad Aminex® 87P carbohydrate column (Hercules, CA, USA), and calculated as percent of theoretical yield based on the composition of the biomass (Table 1).

Pelletization procedure

After packed bed AFEX treatment, biomass was pelletized using a Buskirk Engineering (Ossian, IN, USA) flat die pellet mill. Both PM605 and PM810 model pellet mills were used with 0.25-inch pore size. Untreated biomass was processed first in order to warm the die and roller up to a temperature of at least 75°C. After the temperature was reached, packed bed AFEX-treated biomass at the desired moisture content and particle size was added manually to the pellet mill. Pellet temperature was measured as the pellets were exiting the mill using an infrared sensor. Pellets were collected in a 20-l plastic bucket and allowed to cool on a perforated metal tray. If necessary, pellets were dried overnight in a 50°C convection oven (Blue M Electric Company Class A Batch Oven, Blue Island, IL, USA) to prevent spoilage. The power consumption of the pellet mill was not measured. Accurate measurement of the electrical load of the Buskirk mill requires steady-state operation over extended periods of time, which consumes large quantities of treated biomass. We intend to make these load measurements using biomass treated in the pilot-scale packed bed AFEX system.

Pellet properties were measured after the pellets were dried and cooled to room temperature. Moisture content was measured by placing a preweighed sample of pellets in a 105°C oven overnight and measuring the weight loss. Bulk density was measured by filling a 2-l beaker with pellets and measuring the total weight of pellets added and compensating for the moisture content. Pellet durability was measured via the American Society of Agricultural Engineers 269.4 standard (Temmerman et al., 2006) using a Seedburo pellet durability tester (Seedburo Equipment Company, Des Plaines, IL, USA). Briefly, 500 g of pellets were tumbled in a metal box at 50 rpm for 10 min and then sieved through a #10 mesh to remove any generated fines. The percentage of total biomass that remained in the sieve was determined and recorded as the pellet durability index.

4.2.2 Results & Discussion

General process results

Process conditions during the packed bed AFEX cycle varied only slightly from bed to bed. Starting with biomass at 20–25% moisture at 22–25°C, the presteaming step increased bed moisture to 35–40% and temperature to 80–85°C. At the end of ammonia charging, pressure was 200 psig, top temperature was 35–40°C and bottom temperature was 70–80°C. During the soak period, significant heat was lost from the beds to the surrounding air. By the end of the soak period, top and bottom bed temperatures typically had dropped to 35–40°C. Depressurization dropped the bed pressure to 0 psig, top temperature to 30–35°C and bottom temperature to 10–20°C. By the end of steam stripping, top and bottom temperatures were 80–90°C and moisture was 55–60%.

Ammonia recovery results

During bed depressurization only approximately half of the ammonia charge was released as vapor. During depressurization, the ammonia concentration of the absorbed liquid dropped, while the endotherm of vaporization cooled the bed, until the saturation pressure of the absorbed liquid reached atmospheric. At that point, approximately half of the ammonia charge still remained as residual absorbed ammonia, and steam was added during the steam stripping step to drive further vaporization so that the residual ammonia could be recovered. As Figure 5 shows, more than 90% of the residual free ammonia was recovered as substantially dry vapor having greater than 90% ammonia content, from vertical beds of both corn stover and wheat straw (Stover – V1 and – V2 and Straw – V in Figure 5). Only during removal of the last 10% of free ammonia did the composition of the vapor drop below 90%. In contrast, during steam stripping of a horizontally oriented corn stover bed (Stover-H), less than half of the free ammonia was removed as substantially dry vapor.

The significant difference in steam stripping efficiency between horizontal and vertical beds is evidence of a buoyant effect in the stripping process. Figure 6 shows compositions and densities of ammonia–water vapor mixtures at atmospheric pressure over the range of temperatures encountered during ammonia steam stripping from biomass packed beds. As the vertical beds were stripped, steam entered the top of the bed and condensed on the cold biomass, liberating heat to generate vapor. The density of saturated steam at atmospheric pressure is indicated for reference by the dashed line in Figure 6. As cold, ammonia-rich vapor is released from the bed, that vapor is denser than the incoming steam.

The buoyancy effect due to the density difference between the steam entering the top of the bed and the vapor exiting the bottom of the bed increases the efficiency of the stripping process by segregating the steam and ammonia vapor, so that only substantially dry vapor leaves the bed. When the bed is oriented horizontally, this beneficial buoyancy effect is lost. The incoming steam penetrates rapidly across the top of the horizontal bed and quickly breaks through to the bed exit, so that more than half of the residual ammonia is recovered as wet vapor. Recovery of ammonia as wet vapor is less efficient than recovery as dry vapor, both because more steam is required to completely strip the bed and because more ammonia must be condensed to dry the vapor before recompression. The condensed wet ammonia can be recovered by steam purging the condensate, but purging requires additional energy.

Recovery of ammonia as substantially dry vapor suitable for recompression from vertical packed beds, as shown in Figure 5, significantly simplifies the AFEX process compared with conventional AFEX designs. Direct recompression of the dry vapor stripped from a lead bed, coupled with the absorption of that compressed vapor on a lag bed, eliminates the need for an ammonia recovery dryer or column, or arrangements of ammonia flash and quench tanks, as required in conventional designs described in the literature (Sendich et al., 2008); Laser et al., 2009; Holtzapple et al., 1992). This reduction in equipment requirements yields significant reduction in the capital cost of the system, particularly at the smaller scales anticipated for biomass processing depots.

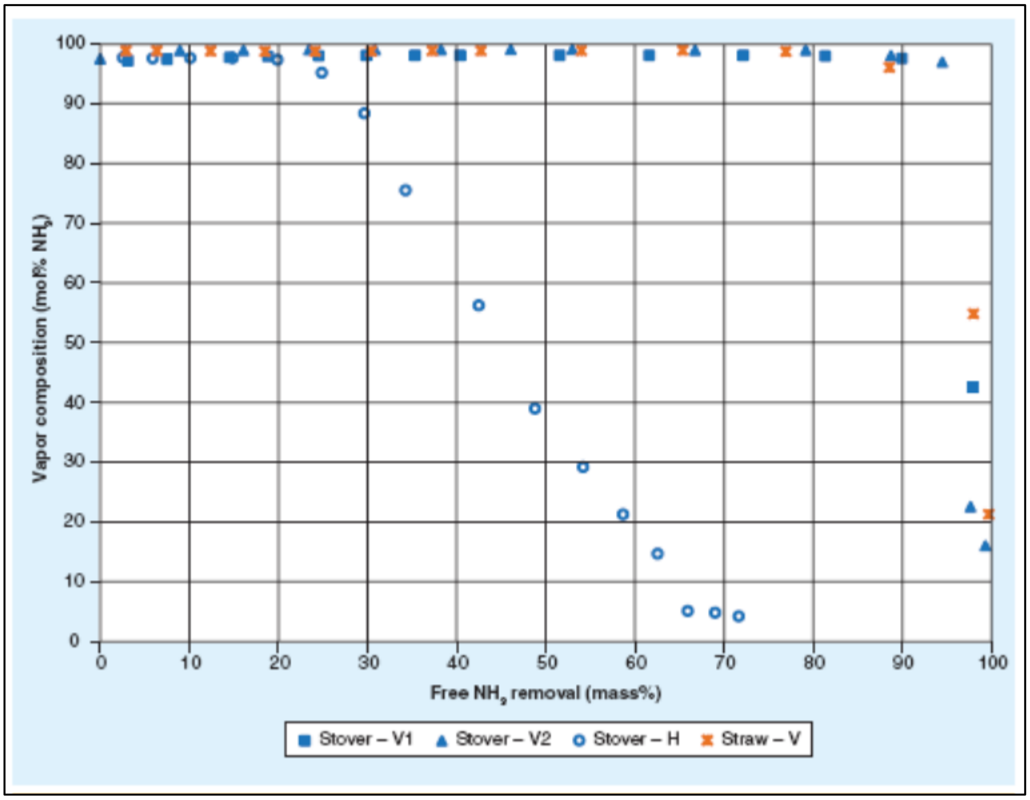


Figure 5. Composition of vapor removed during steam stripping of corn stover and wheat straw packed beds (H: Reactor oriented horizontally; V: Reactor oriented vertically) (Campbell et al., 2013)

Our preliminary analysis of a depot processing 100 tons of corn stover per day shows that greater than 50% reduction in capital cost can be realized using a packed bed system in place of a conventional AFEX design. Note that during the packed bed AFEX cycle, the compressor operates only intermittently, during bed-to-bed ammonia transfer and, consequently, the cost associated with the compressor electrical load is not a significant component of the overall treatment cost.

Ammonia recycle results

Experiments with corn stover in the PB AFEX skid (running 6 beds in series) demonstrated that NH_3 could be charged to the biomass in one bed, stripped off as vapor, and the vapor recompressed and charged to a subsequent bed. More than 95% ammonia was recovered and recycled. We believe that the difference is in ammonia reacting with the biomass and a small amount of ammonia/water condensate remaining within the piping. As the system is scaled up, the latter problem could be greatly reduced leading to nearly complete recovery of unreacted ammonia. Samples of the recovered ammonia were analyzed by GC/MS and no measurable impurity was detected.

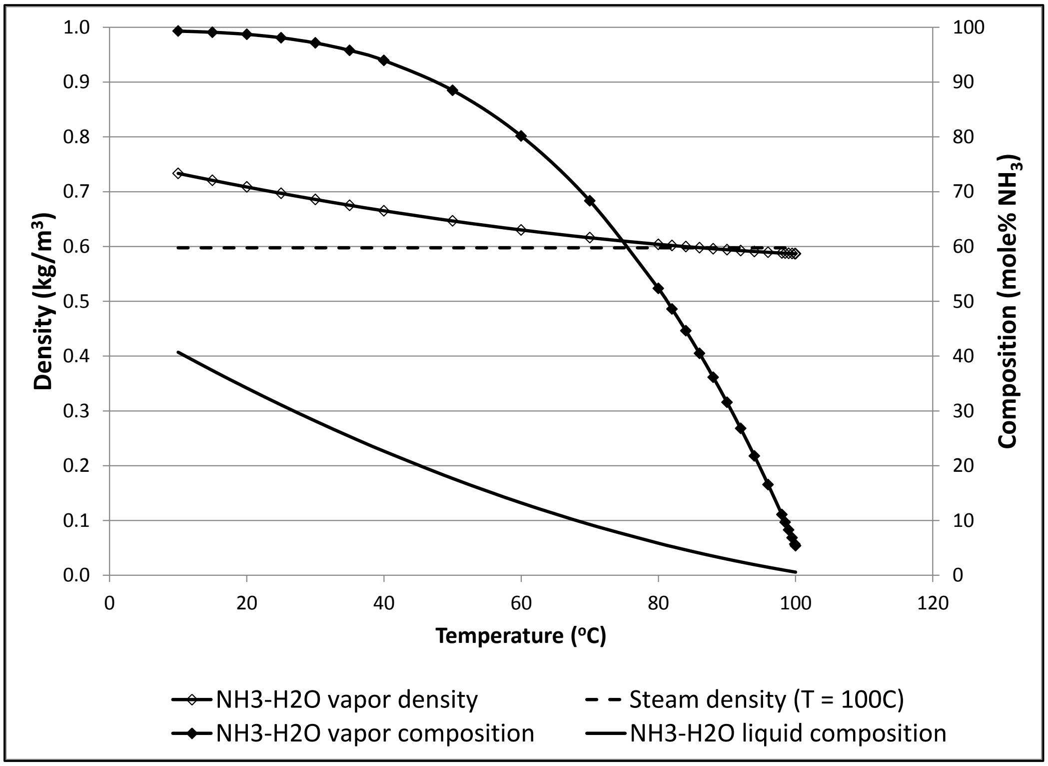


Figure 6. Composition and density of ammonia-water liquid and vapor at atmospheric pressure (data from Tillner-Roth and Friend, 1998)

Enzyme hydrolysis results

Enzyme hydrolysis yields of glucose and xylose from corn stover and wheat straw treated in sequential packed bed AFEX reactors with bed-to-bed transfer of ammonia are shown in Figures 7 & 8. For reference, sugar yields from stover and straw treated in the benchmark stirred batch reactor are also shown. Both stover and straw were as effectively pretreated in the packed bed process as in the stirred batch. As described above, temperature gradients from top to bottom of the beds were observed during ammonia charge and soak steps of the packed bed AFEX cycle, while temperature and concentration gradients were minimized in the stirred batch. Because the vertical beds were charged from the top down, the ammonia concentration was probably highest at the top, where the temperature was lowest, while ammonia concentration was lower at the bottom of each bed, where the temperature was the highest. These two gradients may have compensated for each other, so that when the biomass beds were unpacked and mixed, the composite was uniformly treated, and the hydrolysis results were as good as the stirred batches. It is unclear at this time how this behavior will change as the packed bed AFEX process is scaled up to greater bed lengths. Comparing the stover – bed 1, bed 2 and bed 3 results in Figure 7, the glucose and xylose yields are indistinguishable from bed-to-bed, indicating that sequential beds are treated approximately equally as the ammonia charge is moved from bed-to-bed. More work will be needed to demonstrate that this trend can be continued over longer bed sequences.

In preliminary experiments, enzyme hydrolysis of packed bed AFEX-treated and pelletized stover and straw also gave good yields of glucose and xylose, similar to the yields shown in Figures 7 & 8. Enzyme hydrolysis of the AFEX-treated corn stover pellets at 18 wt% solids loading have shown that glucose and xylose concentrations of 56 and 28 g/l, respectively, can be obtained without increasing enzyme load or hydrolysis time.

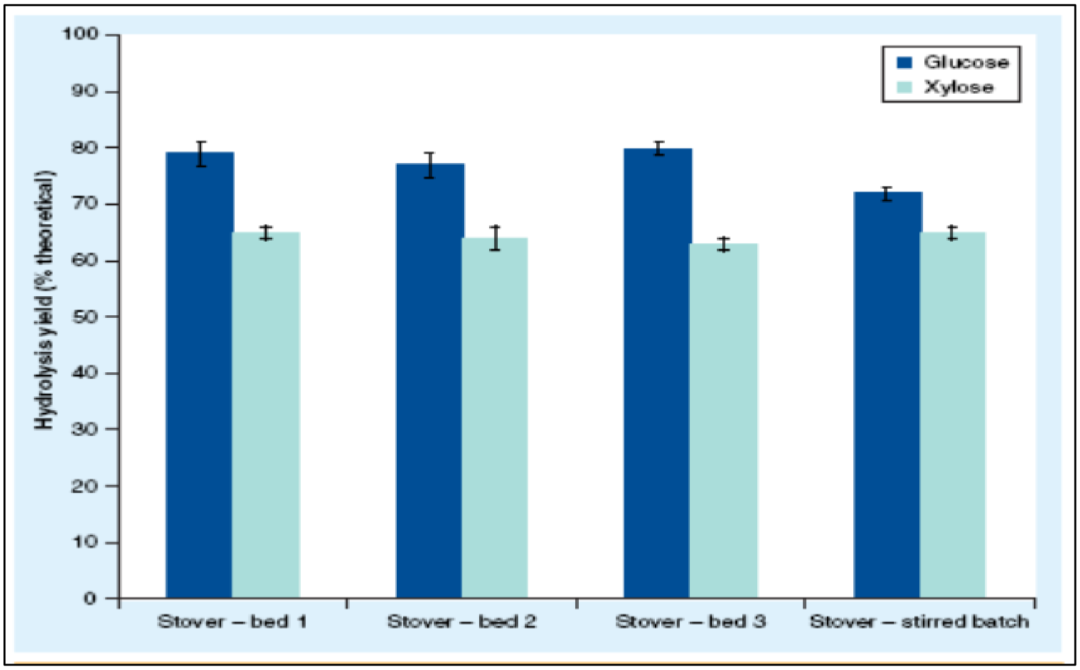


Figure 7. Enzyme hydrolysis yields of glucose and xylose from nonpelletized corn stover treated as sequential beds in the packed bed Ammonia Fiber Expansion reactor system, and in the benchmark stirred batch reactor (Error bars indicate minimum and maximum values of triplicates) (Campbell et al., 2013)

Comparing Figures 7 & 8, it is clear that both glucose and xylose yields were significantly lower from wheat straw than from corn stover. Note that in these hydrolyses, Multifect pectinase was not added and the enzyme cocktail (containing 30 mg of protein per gram of glucan) consisted of 70% Ctec2 and 30% Htec2. With the use of an optimized enzyme cocktail, including addition of pectinase, it may be possible to improve the sugar yields from AFEX-treated straw. Even without the use of optimized enzyme cocktails, the hydrolysis yields from both stover and straw were high enough to demonstrate that packed bed AFEX is an effective pretreatment method for production of biofuels and bio-based chemicals from these agricultural residues. We did not compare enzyme hydrolysis results of pelletized versus nonpelletized AFEX-treated material. The performance of the pelletized material in enzyme hydrolysis will be a key factor in conversion to biofuels and chemicals.

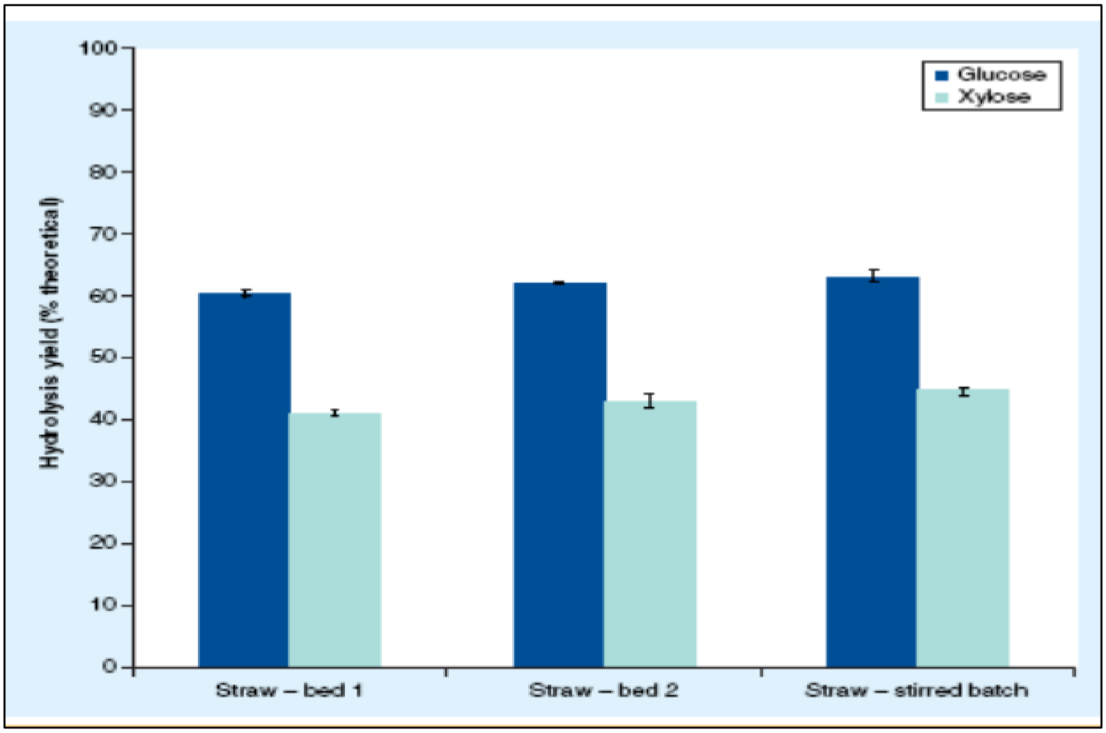


Figure 8. Enzyme hydrolysis yields of glucose and xylose from nonpelletized wheat straw treated as sequential beds in the packed bed Ammonia Fiber Expansion reactor system, and in the benchmark stirred batch reactor (Error bars indicate minimum and maximum values of duplicates) (Campbell et al., 2013)

Pelletization results

One major advantage of using AFEX pretreatment in a depot setting is that pelletization can be performed more efficiently due to the tackiness of the treated biomass, which results from the redistribution of lignin. This is partially seen by the range of moistures and particle sizes at which AFEX-treated material can be pelletized. AFEX-treated wheat straw and corn stover were pelletized at moisture contents ranging between 11 and 50%. In contrast, untreated material would only pelletize at a narrow range of moisture, approximately 15–20%. This expanded range provides greater flexibility at the depot, enabling the depot to produce pellets with different properties or allowing drying to be performed either before or after pelletization. Different properties may be desired for biofuel purposes versus animal feed, for example. AFEX-treated biomass pelletized at low moisture formed very hard pellets with a dark, shiny, smooth outer surface, as seen in Figure 9. AFEX-treated biomass pelletized at higher than 25% moisture content did not have this hard, shiny outer layer, nor did untreated material. Fungal growth was observed on material pelletized at higher than 35% moisture and not dried. In contrast, no fungal growth was observed over a period of 3 months on pellets that were stored at less than 20% moisture. As with corn grain, AFEX-treated biomass may be stored at low moisture in silos for extended periods without significant degradation, microbial growth or mass loss. We expect that material AFEX-treated and pelletized at 25% moisture or less can be successfully stored without further drying.

Figure 9. Packed bed Ammonia Fiber Expansion-treated biomass. (A) corn stover, loose; (B) corn stover, pellets; (C) wheat straw, loose; (D) wheat straw, pellets. Pellets are 0.25 inches in diameter. (Campbell et al., 2013)

AFEX treatment also tended to improve the properties of the pellets, as seen in **Table 2**. Pellet durability was above 90% for all pellets produced except wheat straw at low (12%) moisture content. Furthermore, AFEX tended to improve pellet durability over untreated samples. Both wheat straw and corn stover pellets were more than 99% durable when AFEX-treated, compared with 94–96% durable for untreated pellets. The high durability of AFEX-treated pellets means they are suitable to be stored, handled and shipped without producing many fines. Bulk densities of AFEX-treated pellets were also high, reaching 575 kg/m^3 for corn stover pellets that were produced from dry material. This approaches the bulk density of corn grain, which is approximately 700 kg/m3. When pelletizing wet material, the excess moisture may prevent pore collapse, thus maintaining a relatively low bulk density when dried. AFEX-treated corn stover pellets had higher density than untreated pellets at similar moisture contents, 444–575 kg/m3 for coarsely milled corn stover at 18–20% moisture content, but no difference in density was observed for wheat straw pellets.

Table 2. Bulk density and durability of pellets produced at a variety of conditions. (Campbell et al., 2013)

Treatment	Biomass	Moisture * (%)	Bulk density (kg/m^3)	Durability (%)
Untreated	Wheat straw	20	519	94.3
AFEX	Wheat straw	12	511	85.8
AFEX	Wheat straw	20	544	99.1
AFEX	Wheat straw	50	334	97.2
AFEX	Wheat straw	60	No pellets formed **	
Untreated	Corn stover	18	444	96.6
Untreated	Corn stover	40	No pellets formed **	
AFEX	Corn stover	20	575	99.2
AFEX	Corn stover	40	505	99.8
AFEX	Corn stover	55	No pellets formed **	

* Moisture content is of material entering pelletizer. Pellets were dried to less than 10% moisture prior to performing bulk density and durability tests.

** An attempt was made to pelletize at these conditions, but the biomass did not form pellets

4.2.3 Summary

Chemical pretreatment of corn stover and wheat straw using a laboratory-scale packed bed AFEX-3 reactor system was investigated. The results show that the cycle of presteam, ammonia charge, soak, depressurize and steam strip steps could be repeated with ammonia transfer from bed-to-bed achieved by mechanical recompression of the recovered vapor. Overall, >95% of the ammonia can be recovered and recycled. More than 90% of the residual ammonia removed during the steam stripping step could be recovered as substantially dry vapor when the bed was oriented vertically. This efficient steam stripping performance may be due to a buoyancy effect driven by the density difference between the steam and the colder stripped vapor. Temperature gradients were observed over the length of the bed during the ammonia charge and soak steps. Despite these gradients, the glucose and xylose enzyme hydrolysis yields from the composited biomass recovered from the beds were equivalent to those obtained from stover and straw that were AFEX-treated in a stirred batch reactor. Complete mass and energy balances were calculated and are shown in Section 4.4 regarding the pilot scale design.

The corn stover and wheat straw treated in the packed bed AFEX system formed durable pellets when densified in a conventional pellet mill without added binders. Pellets with good durability were formed from AFEX-treated corn stover at 40% moisture, while untreated stover at this moisture did not pelletize. Based on the efficient ammonia recovery with minimal equipment requirements, good enzyme hydrolysis yields and durable pellet formation observed, the packed bed AFEX approach shows significant promise for chemical pretreatment of corn stover and wheat straw at regional depots.

4.3 Use the AFEX-3 Reactor to Generate Sufficient Quantities of AFEX-treated Material for Applications Testing of Fermentation Production Systems and Initial Animal Feeding Trials

The sections below describe the processes and findings related to study of fermentation and feeding trials using AFEX treated material.

4.3.1 Hydrolysis and Fermentation

4.3.1.1 Experimental

Densification

Both untreated and AFEX-treated corn stover were pelletized using a Buskirk Engineering PM810 (Ossian IN) flat die pellet mill. The die and roller were first warmed to 70˚C by recycling pellets made from untreated material through the die. AFEX-treated biomass was pre-mixed with distilled water to 20% moisture before being added manually to the hopper. The pellets were collected in a 20 L plastic bucket and cooled on a perforated metal tray before drying in a 50˚C convection oven. Pellets were then stored at room temperature in sealed plastic bags until use. A single large collection of AFEX material was well mixed and a portion set aside prior to pelletization; these pellets were used for all experiments comparing pelletized and unpelletized material. A portion of the unpelletized biomass was milled using a CyclotecTM 1093 mill (Foss, Denmark) equipped with a 2-mm screen. Due to a lack of available biomass for comparisons, a separate batch of AFEX treated corn stover was also pelletized and used for experiments that did not require a comparison with unpelletized biomass.

Enzymatic hydrolysis

Enzymatic hydrolysis experiments were conducted at 18% solid loading (w/v, on dry weight basis) with 100 mL reaction volume in 250 mL baffled flasks. In order to prevent microbial growth during hydrolysis, tetracycline and cycloheximide were added to the mixture at 40 mg/L and 30 mg/L, respectively. Samples were adjusted to a pH of 5 using 12.1 M hydrochloric acid prior to enzyme addition and maintained at this pH using a 50 mM sodium citrate buffer. Commercial enzymes provided by Novozymes (Bagsvaerd, Denmark), CTec3 (172 mg protein per g product) and HTec3 (140 mg protein per g product), were each added at 10 mg protein per g glucan. Protein concentration was determined as total nitrogen minus ammonia nitrogen multiplied by 6.25. Due to the high viscosity of the enzymes, they were diluted to 20 mg protein per mL prior to addition to the mixture. The hydrolysis was carried out for 72 hours in an incubator shaker (Model Innova 44, New Brunswick Scientific, Enfield, CT) at 50^{o}C. Agitation was at 250 rpm for the first 24 hours, and then lowered to 150 rpm to ensure thorough mixing. An enzyme blank, containing all inputs except biomass, was also run. Fed-batch addition was performed for the hydrolysis of unpelletized biomass by adding half the total amount of biomass, 12.1 M HCl and enzymes required in the beginning, and the other half after 3 hours.

Sugar Analysis

After 72 hours of hydrolysis, 10-mL hydrolysate slurries were transferred to 15-mL centrifuge tubes (BD Biosciences, San Jose, CA) and centrifuged at 10,000x*g* (Sorvall RC-6+, Thermo Scientific. Waltham, MA) to separate the solids and liquids. The supernatants were filtered through 0.22 µL PES syringe filters to other tubes. Density measurement was performed in

duplicates by weighing the filtered hydrolysates in the 1-mL volumetric flasks on analytical balance to the nearest 0.1 mg.
To prepare the HPLC samples, 1-mL of hydrolysate slurries were sampled using cut pipette tips and transferred into 1.5-mL microcentrifuge tubes. These samples were heated to 90^{o}C for 20 minutes to denature the protein, and then centrifuged at 16,000x*g* (AccuSpinTM Micro, Fisher Scientific, Pittsburgh, PA). The supernatants were diluted 10 fold with deionized water and filtered into HPLC vials using syringes equipped with 0.22 µL polyethersulfone membrane filters.

Monomeric sugars, glucose and xylose, were quantified using a Shimadzu HPLC system equipped with a Refractive Index Detector. The diluted HPLC samples were injected at 10 µL into a SUGAR SP0810 (Pb+ form cation) column (Shodex, Japan) which was heated at 80^{o}C and running at 0.6 mL/min of deionized water. The sugar concentration obtained from enzyme blanks was subtracted from the final result. Hydrolysis yields were calculated using the density method as described in Zhu et al. (2011).

Water absorption

The water retention value (WRV) was used as a measurement of hornification and determined based on the method described by Luo et al. (2011). Briefly, 50 mL centrifuge tubes were packed to approximately one-third full with cotton. Corn stover samples were placed in 125 mL Erlenmeyer flasks with water or enzyme solution (20 mg enzyme per g glucan) at 3% solid loading and rotated at 150 RPM and 50˚C. After the desired time, samples were removed, centrifuged, and rinsed with 30:1 ratio of deionized water. The wet biomass was then placed in the centrifuge tubes packed with cotton and centrifuged at 3000x*g* for 15 minutes. The cotton separated the biomass from excess water during centrifugation. The biomass was then removed and the moisture content measured by drying at 105˚C overnight.

Fermentation

Fermentability of sugars generated from pelleted AFEX treated corn stover was evaluated using *Z. mobilis* 8b (National Renewable Energy Laboratory, Golden, Colorado), following separate hydrolysis and fermentation (SHF) method. *Z. mobilis* is capable of utilizing both glucose and xylose for ethanol production. The process was carried out in a 150L Sartorius fermentor. The fermentor is equipped with two marine style impellers attached to the centric shaft extending from bottom to the middle of the reactor. The target solid loading of pellets was 20% by weight in 80L working volume.

The process was started by adding all the required amount water to the fermentor, sterilizing the fermentor and water, and cooling them to 50° C. Initially half of the required pellets (as is, not sterilized) was added to the fermentor via the top port of the fermentor. The agitation was set to 110 rpm. While mixing, the pH was adjusted to 5.0 using 4M sulfuric acid. After reaching the target pH 20mg of enzyme (10 mg/g glucan of both CTec3 and HTec3; Novozymes) was added to the pellets in the fermentor. The rest of the pellets and enzyme cocktail were added to the fermentor after 2-3 hours of hydrolysis, when most of the pellets were disrupted and there was a good flow in the fermentor. The hydrolysis was carried out for about 72 hr, during the hydrolysis temperature was maintained at 50^{o} C and pH at 5. At the end of the hydrolysis step the temperature and the pH were adjusted to 32° C and 6.0 respectfully. Prior to the inoculation, required amount of sterilized corn steep liquor (target: 1% v/v) and KH2PO4 (target: final concentration of 2g/l) were added to the fermentor. Inoculation was 10% total volume at a cell optical density of 7.5. During the fermentation temperature was maintained at 32° C and the pH at 6.0. The fermentation was carried out for 48 hrs. Samples were taken at 24 and 48 hr time points. HPLC as described by Campbell et al. (2013) was used to analyze samples for sugar and ethanol concentration.

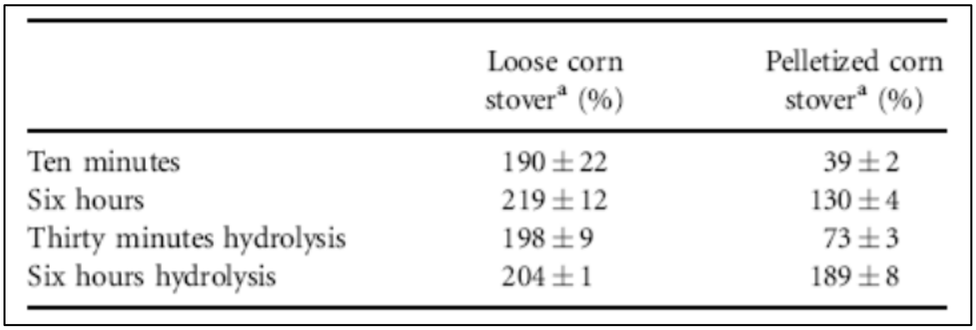
4.3.1.2 Results and Discussion

Dispersion of pellets

Pellets of AFEX treated corn stover were stable and storable. After immersion in water at room temperature, pellets retained their shape, with little biomass dispersing into individual particulates. At 50˚C, more biomass was removed, but the pellets essentially retained their shape during the first 10 minutes of mixing. After three hours, most of the biomass had sloughed off and was freely mixing in the water, although small and less well defined pellets were still observed. By six hours, no pellets were visible. Pellet dispersion happened even faster during enzymatic hydrolysis. After enzymes were added, the solution darkened rapidly due to free biomass particulates and soluble phenolic compounds being liberated from the pellets. After one hour of hydrolysis, some pellets were still visible, although most biomass had been dispersed into the liquid. By three hours, no pellets were visible in the hydrolysates.

The relatively slow liberation of biomass from the pelletized form has a large impact on the amount of water being absorbed by the biomass, as seen in Table 3. Within 10 minutes, the unpelletized (“loose”) corn stover had absorbed twice its weight in water, and did not significantly increase its moisture content in the next 6 hours. In contrast, the total solids from pelletized biomass slowly absorbed water, absorbing only 40% of its weight in the first 10 minutes. After 6 hours, the WRV increased to 130%, which is still significantly lower than the WRV of 200% for the loose biomass. This loss in water retention value, called hornification, is often associated with drying wet biomass (Dini et al., 2004), but can also be caused by pressure (Luo et al., 2011). Likewise, during hydrolysis, the water absorbed by the pellets was low during the initial 40 min, as pellets were not completely disrupted at this point. Once liquefaction is complete, there is little difference between pellets and loose biomass.

Table 3: Water retention value for pelletized and loose AFEX treated corn stover after 10 min and 6 h immersion in water (Bals et al., 2014)



	Loose corn stover[a] (%)	Pelletized corn stover[a] (%)
Ten minutes	190 ± 22	39 ± 2
Six hours	219 ± 12	130 ± 4
Thirty minutes hydrolysis	198 ± 9	73 ± 3
Six hours hydrolysis	204 ± 1	189 ± 8

[a] Values are given as the average of three replicates.

This means that there is more free water in the slurry with pellets relative to loose biomass during the initial stages of liquefaction, which is also the stage where insoluble solids in the hydrolysate are highest. Assuming 18% insoluble solid loading, pellets will have twice as much free liquid as loose milled biomass based on WRV. Visually, at 18% solid loading with loose biomass very little standing water is observed (see Supplemental Fig. S2). Thus, a fed batch approach is required for high insoluble solids loading, but is not needed for pellets. Although the water retention eventually equalizes between loose and pellet biomass during hydrolysis, this does not occur until the insoluble solids content of the slurry decreases to a point allowing easy mixing (Roche et al., 2009).

Characterizing pellet hydrolysis

Pellets of AFEX-treated corn stover were effectively hydrolyzed into monomeric sugars at moderate enzyme loadings, as seen in Figure 10. Yields increased from less than 40% sugar at low cellulase loading to over 70% yield at 20 mg cellulase per g glucan. In comparison, previous studies with AFEX treated biomass used 30 mg protein per g glucan or higher (Garlock et al., 2012; Jin et al., 2012). Sugar yields were 5% less at 10 mg cellulase per g glucan than at 20 mg, which may still be a viable dosage depending on the price of enzymes.

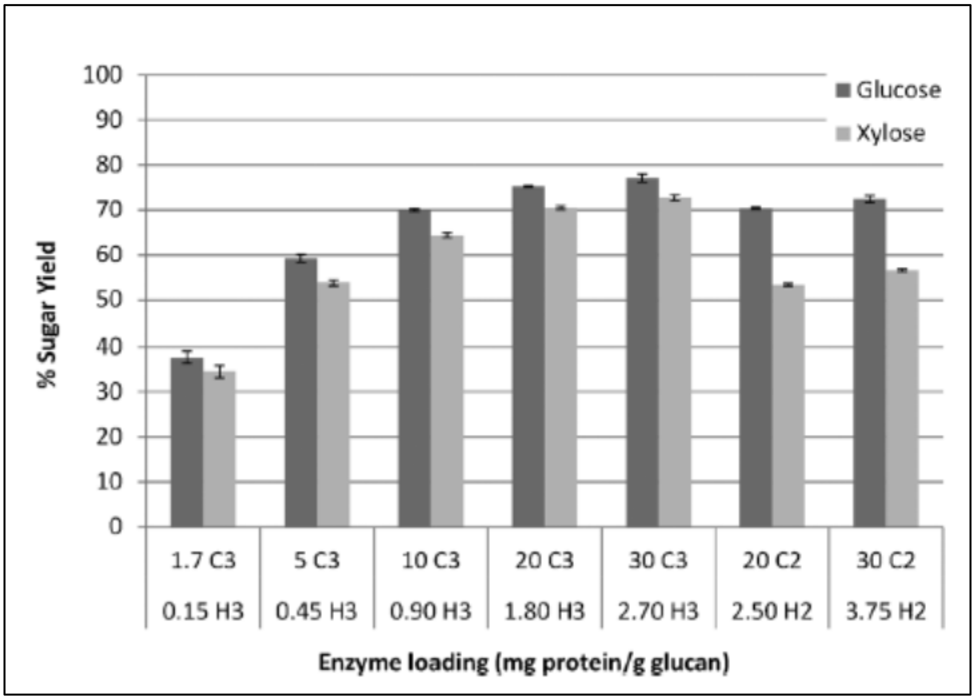


Figure 10: Effect of enzyme loading on glucose and xylose yields of pelletized AFEX treated corn stover. The enzymes used were Novozymes CTec3 as the cellulase and HTec3 as the xylanase. Hydrolysis conditions were 168 hours of hydrolysis at 18% solid loading, 50˚C, pH = 5.0, and 150 rpm (Bals et al., 2014)

Increasing the hemicellulase loading relative to cellulase improved both glucose and xylose yields, as shown in Figure 11. The total enzyme loading was fixed at 22 mg/g glucan. Both glucose and xylose yields increased slightly as the hemicellulase ratio increased to 50% of the total enzymes. This is consistent with previous studies showing xylan removal is critical to effective cellulose hydrolysis in AFEX treated biomass (Gao et al., 2011). Hemicellulose is a complex structure with several different bonds between sugar monomers, and thus designing an optimal hemicellulase mixture is a difficult endeavor. Further improvements in optimizing individual enzyme activities could further lower the total enzyme loading.

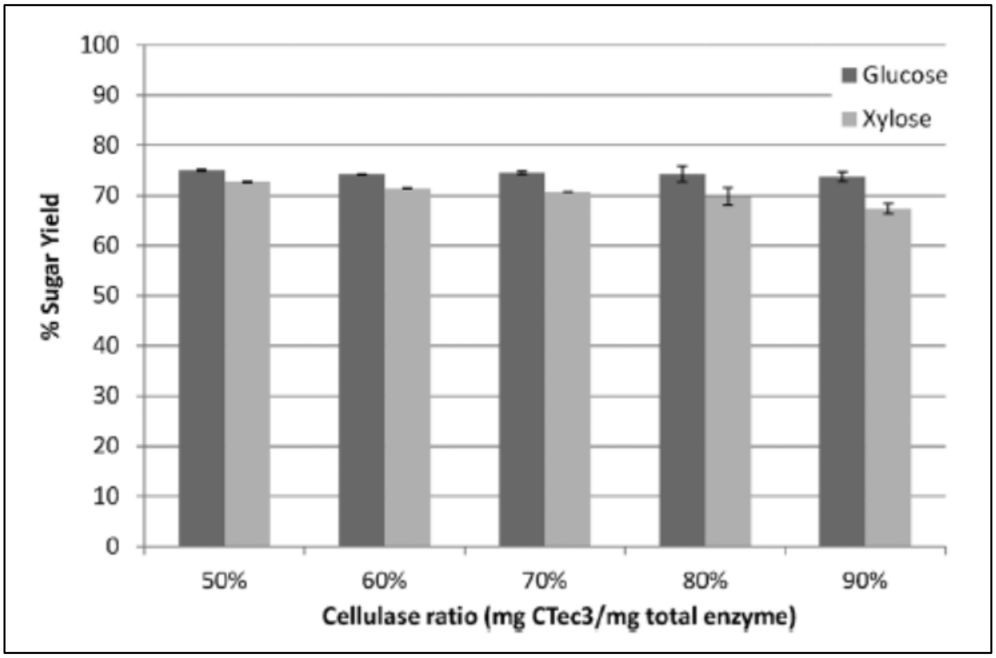


Figure 11 Effect of the ratio of cellulase (CTec3) and hemicellulase (HTec3) on glucose and xylose yields on pelletized AFEX treated corn stover. Total enzyme loading was held constant at 22 mg protein per g glucan. Hydrolysis conditions were 72 hours of hydrolysis at 18% solid loading, 50˚C, pH = 5.0, and 150 rpm (Bals et al., 2014)

Given that pelletization improved mixing at 18% solids, it was hypothesized that higher solid loadings would also be possible. Pelletized AFEX-corn stover was successfully hydrolyzed at up to 36% solid loading, as seen in Figure 12. Biomass could be loaded at 24% solids without a fed-batch approach, but higher solid loadings required two batches of biomass to insure adequate mixing. At 36% solid loading, the hydrolysate remained highly viscous throughout the first 24 hours, and thus may not be suitable commercially without a strong mixer. In general, yields decreased slightly as solid loading increased, most likely due to sugar and lignin inhibition (Kristensen et al., 2009). Despite this yield loss, sugar concentration increased greatly, approaching 100 g/L glucose and over 50 g/L xylose at 30% solid loading. If there is no loss of productivity during fermentation, then ethanol titers approaching 7% (w/v) can be obtained.

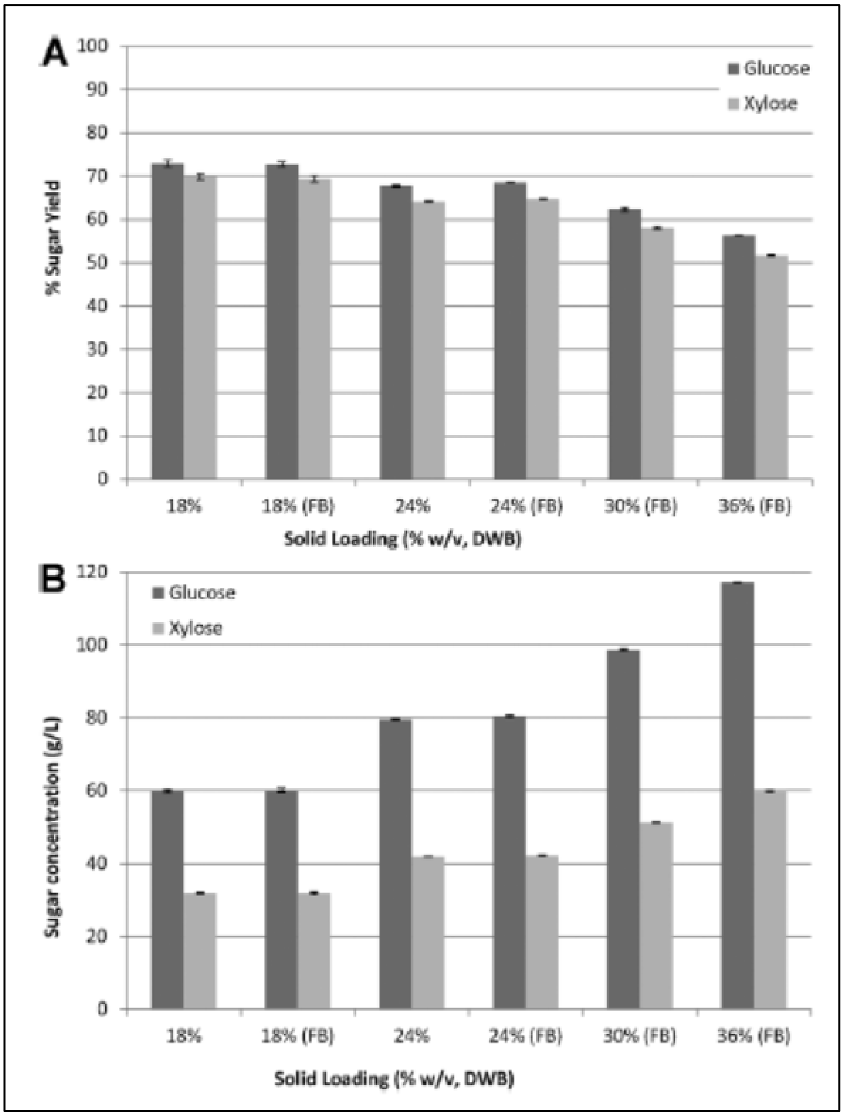


Figure 12. Effect of increasing solid loading on glucose and xylose yields (A) and concentration (B) on pelletized AFEX treated corn stover. Hydrolysis conditions were 72 hours of hydrolysis, 10 mg CTec3 and 10 mg HTec3 per g glucan, 50˚C, pH = 5.0, and 150 rpm. FB = Fed batch addition, with 50% of the total biomass and enzyme added initially and 50% after 3 hours of hydrolysis (Bals et al., 2014)

Comparison of loose vs pelletized biomass

Pelletization can cause several physical changes within the biomass that might impact fiber hydrolysis, In particular, particle size reduction in the pellet mill can improve sugar yields (Dasari and Berson, 2007) and decreased water retention values can reduce sugar yields (Luo et al., 2011). In addition, the decreased water retention improves mixing during the initial liquefaction step, which may improve hydrolysis. An attempt to separate these factors is shown in Figure 13. Low solid loading was used to negate the impact of mixing, as the free liquid to insoluble solids ratio is similar for both pelletized and loose biomass. In addition, the loose biomass was also milled to 2mm to mimic the grinding that occurs during pelletization. There was no way to separate the change in water retention from pelletization.

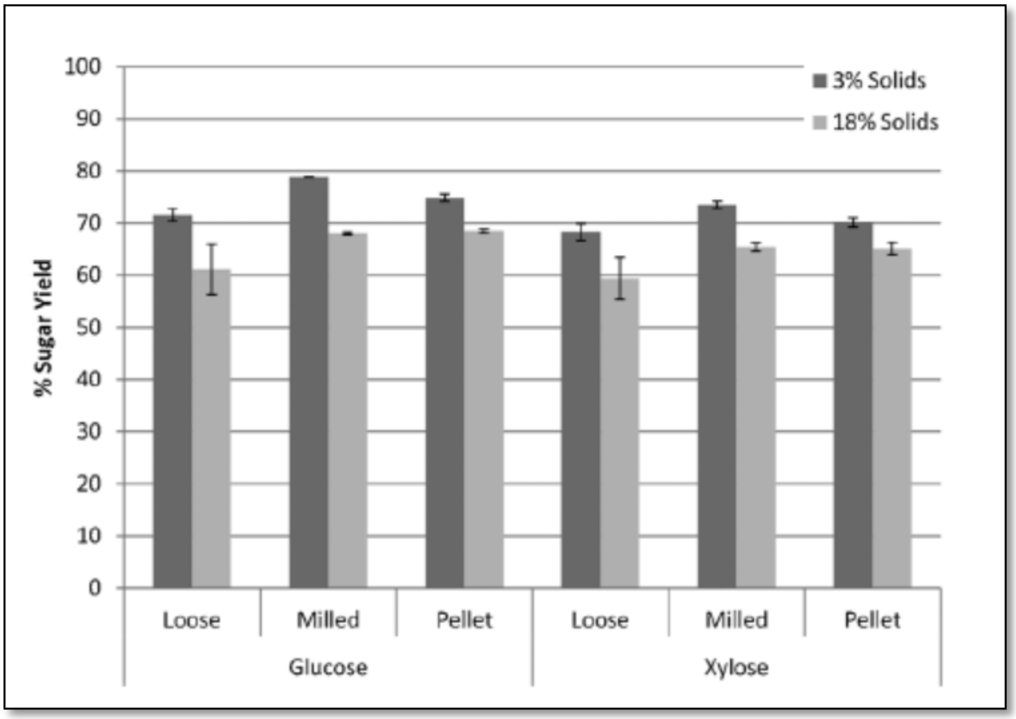


Figure 13. Comparison of pelletized, loose, and loose milled AFEX treated corn stover at low (3%) and high (18%) solid loading. Hydrolysis conditions were 72 hours of hydrolysis, 10 mg CTec3 and 10 mg HTec3 per g glucan, 50˚C, pH = 5.0, and 150 rpm (Bals et al., 2014)

Milling the loose biomass increased digestibility at both low and high solid loading. The glucose yield increased by 7% and the xylose yield by 5% due to milling the biomass at both low and high solid loading. In contrast, pelletization also increased the yield of both glucose and xylose compared to unmilled corn stover, but there was a confounding factor caused by solid loading. Milled and pelleted corn stover produced identical glucose and xylose yields at high solid loading, but yields for milled material were slightly higher than pelleted stover at low solids.

This suggests that all three factors: improved mixing, decreased particle size, and hornification all play a role in changing sugar yields. Improving mixing and decreasing the particle size both serve to improve sugar yields over unpelletized corn stover, while hornification serves to decrease sugar yields. Of these changes, the hornification effect appears to be the smallest factor. Luo et al. (2011) observed a reduction in enzymatic digestibility for samples that were hornified due to pressing and drying. However, the reduction in enzyme digestibility did not occur until WRV decreased to below 110%, whereas water retention value in AFEX treated pellets was 130%. It is also possible that particle size reduction is not as complete in the pelletizer compared to the knife mill used. In this case, the impact of hornification is less than observed in this experiment. In total, however, pelletization improved the extent of hydrolysis compared to unpelletized material at high solid loading.

Previous research has suggested that pelletization does not significantly change the cell wall composition of the biomass, but may reduce hemicellulose slightly (Kumar et al., 2012; Theerarattananoon et al., 2012; Rijal et al., 2012). Similar results were observed for loose and pelleted AFEX treated biomass. A small but significant decrease in xylan content was observed after pelletization. Interestingly, this decrease was observed in both polymeric xylan as well as soluble xylo-oligomers produced during AFEX. Xylan may be reacting with lignin during the pelletization process, making it unavailable for sugar hydrolysis. Glucan may have decreased slightly, but the difference is not significant.

The rate of hydrolysis at 18% solid loading is similar between loose and pelletized biomass, as seen in Figure 14. The largest difference is due to fed batch loading. When all pellets are present from the onset of hydrolysis, the rate of sugar production is naturally higher than when only half of the pellets are present during the first 3 hours (11.3 and 5.5 g/L/h for glucose and xylose compared to 6.7 and 3.1 g/L/h for fed batch). After 3 h, the total glucose and xylose concentration in the pellet hydrolysis without fed batch is 48 g/L compared to only 28 g/L for the fed batch hydrolysis. In contrast, the fed batch pellets and loose material both had similar rates of hydrolysis. However, sugar concentration for fed batch pellets was slightly but significantly ($P>0.05$) higher than loose biomass between 6 and 12 hours of hydrolysis. This further suggests that pelletization can increase sugar yields by increasing the free water present and improving mixing. The second addition of biomass occurs at 3 hours, and so the insoluble solid content is highest for the fed batch additions between 3 and 12 hours. However, once liquefaction is complete, all three samples reached the same end point in both glucose and xylose concentration. It does not appear likely that pelletization can substantially reduce the time of hydrolysis. However, if a hybrid saccharification and fermentation approach is used (Aden and Foust, 2009), the increased sugar production during liquefaction may improve the final biofuel yield.

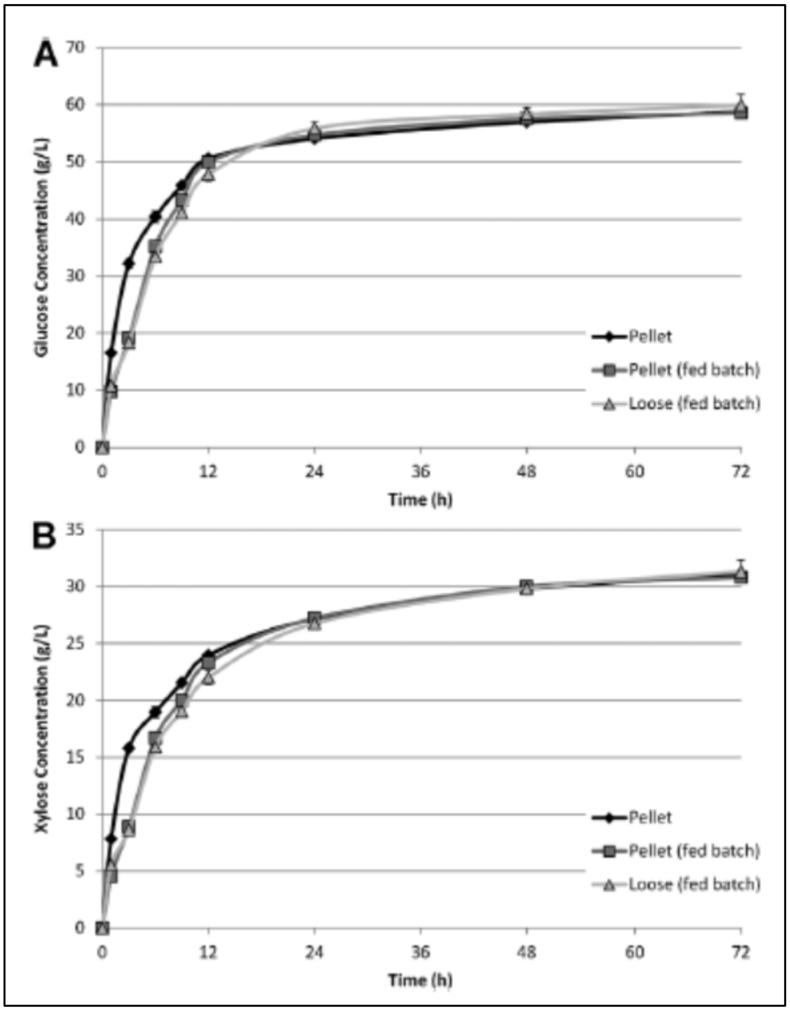


Figure 14: Rate of hydrolysis of glucose (A) and xylose (B) for pelletized and loose AFEX treated corn stover. Both a single batch and fed batch of pellet loading is shown. Hydrolysis conditions were 18% solid loading, 10 mg CTec3 and 10 mg HTec3 per g glucan, 50˚C, pH = 5.0, and 150 rpm (Bals et al., 2014)

Impact of pelletization

We have demonstrated that pellets of AFEX-treated corn stover can be effectively hydrolyzed and fermented into multiple products at high solid loading. During the pelletization process, the particle size is reduced further and the lignin acts as a binder under high pressure. The lignin may act as a hydrophobic barrier, slowing the rate of water absorption. In addition, there may be some pore collapse due to compression of the fiber, as evidenced by the decreased water absorption capacity. While decreasing the particle size generally improves hydrolysis performance (Dasari and Berson, 2007), pore collapse and decreased water absorption can negatively impact enzymatic hydrolysis (Luo et al., 2011).

Thus, the improvement in mixing and particle size reduction may be the primary causes of improved enzymatic hydrolysis via pelletization. This is demonstrated in the difference between 3% and 18% solid loading hydrolysis. Densified biomass can be added to an enzyme solution at 18% solid loading without requiring fed-batch addition and maintaining a large amount of free water. This allows for even mixing at the onset of liquefaction, thus insuring a steady pH in the solution and reducing the possibility of enzyme deactivation. Likewise, using densified biomass allows for more effective mass transfer of sugar and other soluble components away from the insoluble fiber and bound enzymes. The increased residence time due to eliminating fed-batch loading does not appear to be a significant factor, as seen in Figure 14. The improvement in mixing, as well as the reduction in particle size, is apparently sufficient to overcome the decreased water absorption capacity.

While pelletization of lignocellulosic biomass has traditionally been considered for the purpose of improving logistics (Sokhansanj and Hess, 2009) the ease of mixing during liquefaction for pellets of AFEX treated biomass may also simplify reactor design. Various liquefaction reactor designs have been proposed for liquefying high solid biomass slurries, including horizontal paddle mixers (Jorgensen et al., 2007), vertical high shear mixers with anchor and/or ribbon impellers, or a vertical plug flow reactor (Humbird et al., 2011). However, these designs are either expensive, cannot be scaled to high volumes, or unproven. In contrast, liquefaction of pelletized AFEX treated biomass can be performed in conventional stirred tank reactors using a marine or pitched blade turbine due to the high free water to insoluble solids ratio. To test this, pellets were loaded in a 5-L reactor equipped with a single marine impeller at 18% solid loading and the course of hydrolysis observed. Pellets began to break apart rapidly and all biomass could remain in suspension with an impeller speed of 600 rpm. Within 2 h, all pellets were fully disrupted and the apparent viscosity had decreased to a point that 150 rpm was sufficient to keep biomass in suspension. In contrast, loose biomass could not immediately be fully suspended even with only half the initial biomass. After the second batch was added, it required several hours to reduce the viscosity to the point that all biomass could be suspended, even at 1,000 rpm.

Stirred tank reactors are relatively inexpensive, scalable, and may be identical to the reactors used for hydrolysis and anaerobic fermentation. In addition, there would be no need for a fed batch system, which should ease mixing and reduce contamination, and there is the potential to increase solid loading in order to increase sugar concentration. Viamajala et al. (2009) speculated that severe pretreatments that produce hornification could lower the viscosity and therefore power requirements for mixing biomass due to the increased free water present. Given the extreme differences in free water available during initial liquefaction for pellets and loose biomass, pelletization could significantly reduce power requirements for mixing at the biorefinery.

Fermentation

Glucose and xylose yields at 80 L scale were both superior to identical pellets hydrolyzed at the shake flask scale, possibly indicating improved mass transfer or decreased shear stress in the fermentor. Fermentation performance was as expected. Production of ethanol using *Zymomonas mobilis* utilized all available glucose in 24 hours and consumed 80% of the xylose in 48 hrs (Figure 15). Incomplete xylose utilization is a limitation of the research strain of *Z. mobilis* that was used and not due to poor enzyme hydrolysis of the AFEX pellets. The ethanol production was 45 g/L, equivalent to fermentation of pure sugars (glucose and xylose). Similar results were obtained in fermentation of AFEX-treated corn stover by *Actinobacillus succinogenes* to produce succinic acid (data not shown).

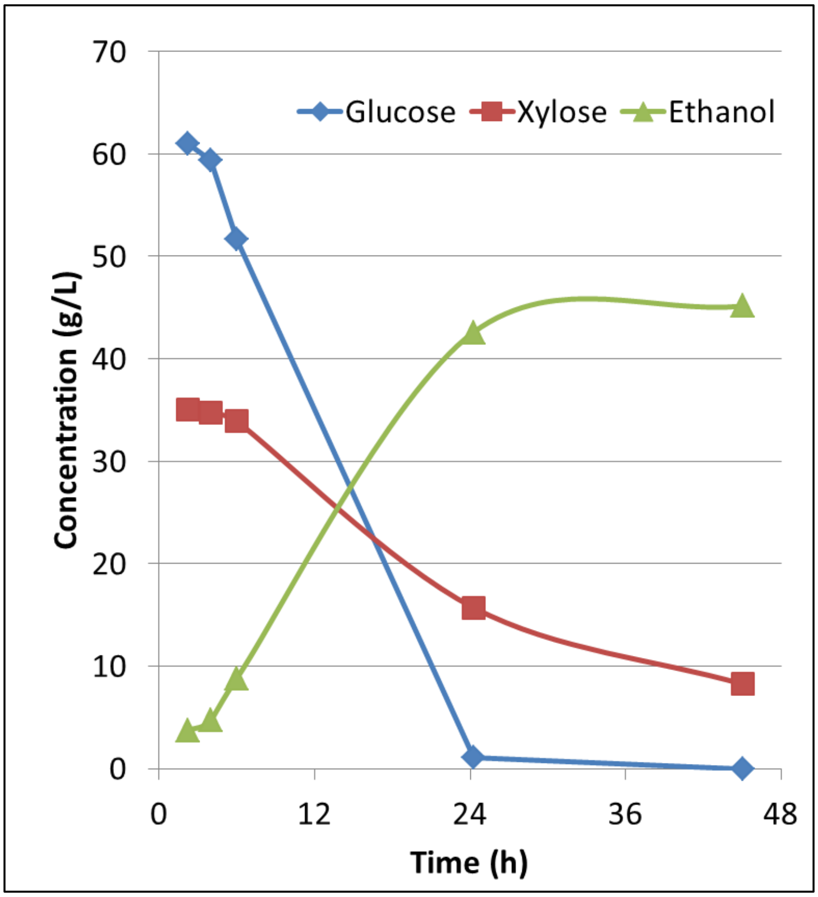


Figure 15: Ethanol production during fermentation of AFEX-3 pellets at the 80 L scale

4.3.1.3 Summary

Pelletized AFEX treated corn stover was shown to be easily mixable and digestible at high solid loadings during enzymatic hydrolysis. Using 20 mg enzyme protein per g glucan, over 70% of the total sugars were liberated in monomeric form at 18% solid loading and 72 hours. Hydrolysis yields were virtually identical between pelletized and milled, non-pelletized AFEX-treated stover, while pelletization improved sugar yields over unmilled material by approximately 3%. Thus, AFEX-treatment at a local depot followed by pelletization and transportation to a centralized biorefinery may be a viable solution to the logistical issues with biofuel from herbaceous cellulosic materials. It was shown that AFEX corn stover pellets can be efficiently utilized as a feedstock for fermentations to produce both fuels and chemicals.

4.3.2 Animal Feed Studies

Alkali treatments to enhance the nutritional value of low quality grass hays and cereal crop residues are well known. Treatment of these materials with anhydrous ammonia, sodium hydroxide, calcium hydroxide or other strong bases can degrade some linkages between lignin and hemicellulose in the fiber, or cell walls, of grasses. Ammonia fiber expansion (AFEX) is an ammonia-based process for improving the susceptibility of lignocellulosic materials to microbial fermentation or enzymatic hydrolysis. Calcium oxide (CaO), commonly known as quicklime, is currently being evaluated as a fiber treatment. When water is added to powdered CaO (quicklime) it hydrates and forms CaOH (hydrated lime or calcium hydroxide). Calcium oxide is more reactive than CaOH and generates heat when mixed with water. To treat stovers or straws, 5% CaO or CaOH is added to the fiber source and water is added to bring the moisture to 50% to allow chemical reactions and penetration of alkali into fiber. The material must be stored 5 to 7 days to provide time for adequate reaction to occur.

4.3.2.1 Experimental

In Situ Digestibility Evaluation of AFEX Pellets

AFEX feed was evaluated *in situ* compared to untreated corn stover from the same source. Two ruminally fistulated steers fed a mixed diet had untreated corn stover (Control) or AFEX-treated stover (AFEX) incubated in the rumen for 24 and 48-hours, and neutral detergent fiber (NDF) digestibility was measured. We also evaluated the *in situ* digestibility of corn stover that originated from the same source and was treated with either 5% calcium oxide or AFEX.

Palatability and Digestibility Trial in Sheep

The objectives of this experiment were to:

1. Determine the intake and digestibility of AFEX treated stover using young lambs,
2. Measure the intake and digestibility of calcium hydroxide (**CaOH**) treated stover as a alternative method for improving the feeding value of fibrous feeds,
3. Compare the intake and digestibility of AFEX and CaOH treated stovers to the control untreated corn stover (**Control**) to assess improvement, and
4. Evaluate the standard digestion trial protocol for the initial animal evaluation of treatments that may enhance the digestion and intake of low quality, high fiber sources.

Corn stover bales were obtained from Cherry Farms, Greenfield, IN that had been stored dry and in a barn. The AFEX treated stover was generated in the 10 kg/day 3-bed reactor. The CaOH treated stover was generated by mixing 395 lb of ½ in ground stover with 19 lb of CaOH and 315 lb of water. The mixture was stored in sealed fiber drums for 7 days. Mixture was removed from drums, windrowed on concrete floor for 4 days with fans circulating air to improve drying. A portion of this air-dried material (353 lb) was used to make the treatment mixture. Each material was mixed with supplemental feeds to make a diet mixture that met the protein and mineral requirements of growing lambs (Table 1). In addition, a reference or standard (**StdRef**) mixture was formulated that contained additional sources of materials to be improved by potential treatments. All mixtures were pelleted though a 30 hp ring die pellet mill (CME Model #ECO-R30, Night Hawk Mfg & Repair Inc., W7911 Oakwood Rd, Waupun, WI 53963) without steam to manufacture pellets that were 12 mm in diameter and 16 to 20 mm in length. All diets were stored in drums in cold-storage (2.8 °C) until they were fed. The StdRef was fed to all lambs prior to their placement in metabolism crates, and the intake and digestion of this diet was determined for all lambs during the covariate period of the trial. Only a small amount of AFEX material was available (about 100 kg) and this limited the number of animals on this treatment and the length of the intake and digestion trial.

All animal handling, care, and treatment followed standard operating procedures based on the Ag Guide, 3rd edition. Lambs were introduced to their treatment diet for two days in pens during the pre-trial period so they would be acquainted with the treatment diets. Then, they were fed the Standard Reference Diet for 7 days while in pens. Lambs were placed in individual elevated metabolism crates (43 by 131 cm). Lambs were tethered in the crates with free access to feed and water. Feces were collected on a screen under a grated floor, which allowed urine to pass though. The StdRef diet was fed for an additional 6 days while lambs adjusted to the crates and achieved ad libitum intake. During following 5 days, ad libitum intake was measured and total collection of feces was measured and sampled to determine intake and digestibility of StdRef by all lambs.

After the StdRef measurements were taken, each lamb was transitioned to its treatment diet over two days and then fed their assigned treatment diet to obtain ad libitum intake for 4 days before measurements and collections were made to determine ad libitum intake and digestibility of the treatment diets. Due to limited amounts of AFEX and the high feed intake of this treatment, the duration of adjustment period and digestibility collection period were minimal (intake and digestibility information were only obtained for 4 days.

Fourteen lambs were available for this study, which ranged in weight from 20 to 36 kg (average = 29.4 ±4.7 kg). Five lambs were used for Control and CaOH-treated corn stover treatments and 4 lambs were used for the AFEX-treated stover treatment. Lambs were ranked by starting body weight and the two heaviest lambs were described as block 5 and one of these lambs was assigned to Control or CaOH treatments. The remaining twelve lambs were divided into four blocks of three lambs. One lamb in each block was randomly assigned to Control, CaOH or AFEX treatments.

Initial dry matter (**DM**) was determined by drying all samples of feeds, refusals and feces for 48 h in a forced draft oven at 60 °C and allowing them to equilibrate at ambient temperature and humidity for 24 h. Chemical analyses were performed by Cumberland Valley Analytical Services after grinding the samples as-received through a 1-mm screen using a cyclone mill. Laboratory DM of ground samples was determined by drying for 3 h in a forced draft oven at 105 °C. Crude protein (**CP**) was determined as 6.25*N in the sample that measured by combustion (Leco FP 528 Combustion analyzer, St Joseph, MI). Neutral detergent insoluble CP (**NDICP**) was determined as 6.25*N (measured by combustion) in the neutral detergent fiber residue when extracted with sodium sulfite. Acid detergent insoluble CP (**ADICP**) was determined as 6.25*N (measured by combustion) in the acid detergent fiber residue. Total ash was determined by combustion of samples at 600 °C.

Amylase-treated neutral detergent fiber (**aNDF**) was determined by the method of Mertens (2002), with the modification that fiber residues were collected on 7-cm Whatman glass fiber filters (type 934-AH with 1.5-um particle retention) in a California Buchner funnel instead of using Gooch crucibles because the larger surface area improves filtration. Ash-free aNDF organic matter (**aNDFom**) was determined by subtracting the ash in aNDF residues (Mertens, 2002). Acid detergent fiber (**ADF**) and lignin (**SLig**) was determined by a modification of the method by Van Soest (1973). Acid detergent fiber was recovered on 7-cm Whatman glass fiber filters (type 934-AH). Fiber residue and filter was transfer to a capped tube and approximately 45 ml of 72% sulfuric acid was added. Tubes are gently agitated for 2 hours to insure that all fiber material is continually washed with acid. The contents of the tube after incubation in acid is filtered onto a second filter (Whatman 934-AH) which is then rinsed, dried and weighed. Filters and lignin residue were ashed for 2 hours in a muffle furnace and residues were weighed to determine lignin concentration in DM.

In vitro gas production (IVG) was measured manually at 2, 4, 8, 12, 24, and 48 h by the method used at the U.S. Dairy Forage Research Center. This method is a modification (Weimer, et al, 2005) of the in vitro digestibility method of Goering and Van Soest (1970). Modification include: (1) use of 50 ml serum vials that provide about 48 ml of headspace when fermenting 0.1 g of substrate with about 10 ml of media and inoculum, (2) vials were crimp-sealed with stoppers (septum stoppers 20mm, Bellco Glass Inc., catalog number 2048-11800A) that were used for only three runs to minimize leakage due to repeated puncture, (3) buffer solution, without trypticase, was purged with CO_2 for an hour before storage overnight. The morning of inoculation, buffer was removed from cold storage, trypticase was added, and the media was purged with CO_2 for at least two hours while vials are being prepared and media was warmed to 39 °C. After adding 6.7 ml of media, vials were purged with CO_2 prior to inoculation, (4) 0.3 ml of reducing solution containing 48ml deionized H_2O, 0.312 g L-cysteine hydrochloride monohydrate, 0.312 g sodium sulfide crystals (crystals are rinsed in deionized H_2O and dried before weighing) and 1.95 ml 1N NaOH, (5) inoculum was prepared from strained ruminal fluid and blended solids from 3 lactating cows receiving a total mixed ration containing alfalfa and corn silage plus concentrates (200 ml of strained rumen fluid was combined with 400 ml of strained buffer that was blended with 100 g of squeezed solids from each cow), (6) fermentations occurred in a warm room at 39° C, (7) vials were weighed empty, and before and after inoculation, and (8) gas pressure was measured using a digital meter (Model SDPGB0015PGS by SenSym) by puncturing each stoppered vial and recording the pressure. Pressure measurements were corrected for the initial pressure in each vial and loss of gas with each measurement. Gas production was adjusted for blank gas production due to inoculums only, small deviations in inoculums weight, differences in individual vial headspace, and substrate dry matter weight. Gas production was determined on the pelleted mixtures that were ground through a cross-beater mill (Model SK100; Retsch GmbH, Haan, Germany) with a 1-mm screen.

Five daily samples of the Reference Standard diet and four daily samples of treatment diets were taken during the digestion trial and analyzed individually. Differences in diet composition were detected assuming completely random experimental design. The data was analyzed using the Mixed procedure of SAS (SAS Institute Inc., Cary, NC) with Treatment as a Fixed effect and Day of Sampling as a random effect.

Beef cattle trial

To fully derisk the animal feed application, the performance of AFEX-treated biomass needs to be tested and evaluated in beef cattle feed trials. A trial was begun in September 2013 in collaboration with Michigan State University and a major animal nutrition company and is expected to be completed in March of 2014. MBI is providing 10 tons of AFEX-treated corn stover pellets for the trial.

The study is designed to be indicative of feedlot animal performance and will determine if AFEX-treated corn stover can be substituted for corn grain as an energy component in feeding rations for growing-finishing beef cattle. Weight gain and carcass meat quality will be determined at the end of a 160 day feeding period.

Hypothesis: AFEX-treated corn stover will yield equivalent weight gain and carcass quality compared to standard ration feed. ***Milestones:*** Determine the performance of AFEX-treated corn stover compared to corn grain in the diet of growing-finishing beef cattle as measured by weight gain and carcass quality (completed by December 31, 2013).

Expected outcomes: AFEX-treated corn stover fed substituted at 30% level for corn grain will produce equivalent weight gain and carcass quality as standard beef cattle feed rations.

Twenty four Holstein beef steers (900 lb) are being utilized to evaluate the effects of feeding AFEX-treated corn stover on performance of growing-finishing cattle. Cattle are housed at the Beef Cattle Teaching and Research Center located at Michigan State University. Steers are individually penned and fed. Upon arrival, steers received routine vaccinations and parasite control. A growth-promoting implant was administered. Steers were blocked by weight into 12 blocks and allocated into one of two treatments. The two treatments are: standard feedlot diet, and 30% AFEX-treated corn-stover pellets. AFEX-treated corn stover will replace a percentage of corn in the diet. The basal diet includes 51% high moisture corn, 30% modified distiller's grain with soluble, 15% corn silage, and 4% of a protein-mineral supplement. The corn stover diets include 36% high moisture corn, 20% modified distiller's grain with soluble, 30% corn stover (treated), 10% corn silage, and 4% of a mineral-vitamin supplement. Rumensin™ is included in the supplement to provide 250-300 mg/hd/d. All diets are fortified to meet the protein, mineral and vitamin requirements as defined by NRC (1996). Feed samples are collected weekly, composited monthly and analyzed for nutrient content. Cattle are weighed at 28 d intervals. The initial and final weights will be the average weight taken on two consecutive days immediately before harvest.

Cattle will be harvested at the MSU Meat laboratory within a two week period. At harvest, liver abscess incidence and hot carcass weight will be recorded. After a 24-48 h chill, routine carcass evaluation (12th rib backfat thickness, ribeye area, and KPH) will be performed. Marbling will be recorded. Data to be collected will include animal performance at 28 day intervals and overall (weight gain, dry matter intake, feed conversion efficiency), calculated energy values for the two treatments, and carcass data by treatment.

4.3.2.2 Results and Discussion

In Situ digestibility evaluation of AFEX pellets

As shown in Table 4 AFEX processing reduced the NDF content of the corn stover by 28% and improved NDF digestibility by 94% and 60% at 24 and 48-hr of incubation, respectively. The combination of reducing NDF concentration and increasing NDF digestibility resulted in a reduction in the indigestible NDF fraction by 31% at 24-hours and 73% at 48-hours of incubation.

Table 4. *In situ* NDF digestibility of untreated and AFEX treated corn residue

Item	Control	AFEX	SE	*P*-value
NDF concentration, %	74.2	53.1	-	-
24-h in situ values				
NDF Digestibility, %	33.0	64.1	1.11	<0.01
Indigestible NDF, %	49.7	19.0	0.64	<0.01
48-h in situ values				
NDF Digestibility, %	50.9	81.2	0.97	<0.01
Indigestible NDF, %	36.4	9.7	0.55	<0.01

As shown in Figure 16 both calcium oxide and AFEX appear to reduce the amount of stover remaining in the *in situ* bags at all incubation points. While the data are not corrected for ash, treatment with AFEX appeared to be more effective in improving in situ disappearance than calcium oxide.

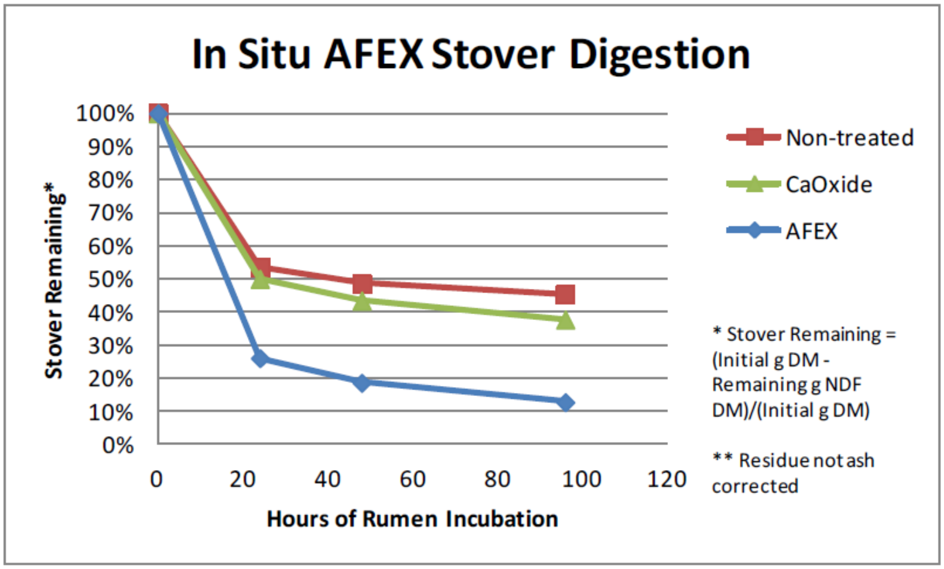


Figure 16. *In situ* digestibility of corn stover treated with 5% calcium oxide or AFEX

Palatability and digestibility trial in sheep

Pelleted diets consisting of 80% corn stover that was untreated (Control), treated with calcium oxide (CaO), or AFEX was fed to lambs (BW = 65 ± 10 lb.) and total tract digestibility was measured (Table 5).

While treatment with calcium oxide reduced the NDF content of the diet, it was similar to the Control in all digestion parameters. Treatment with AFEX also reduced dietary NDF concentration, but concomitantly increased the digestibility of NDF. Intake of organic matter and NDF also increased, resulting in greater intake of digestible organic matter. We would expect this to translate into improved animal performance.

Table 5. Digestibility of corn stover treated with calcium oxide (CaO) or AFEX fed to lambs

Item	Control	CaO	AFEX	SE	*P*-value
Organic Matter					
Intake, % BW	3.68^b	3.75^b	5.32^a	0.27	<0.01
Digestibility, %	49.60	49.80	52.60	1.10	0.10
Digestible Intake, % BW	1.82^b	1.86^b	2.79^a	0.14	<0.01
Neutral detergent fiber					
Dietary concentration, %	59.50^a	54.90^b	49.80^c	0.50	<0.05
Intake, % BW	2.50^b	2.44^b	3.02^a	0.17	<0.01
Digestibility, %	45.30^b	44.70^b	51.00^a	1.50	0.02

In vitro gas production (Table 6) of the ground feed mixture pellets was measured in two *in vitro* runs (IVRun1 and IVRun2) that were conducted 27 d apart. In IVRun1, manual gas pressure measurements were taken at 4, 12, 24 and 48 h after inoculation. In IVRun2, measurements were taken at 2, 4, 8, 12, 24 and 48 h. In IVRun1, order of inoculation had a negative impact on IVGP ($P < 0.003$) for all times, except 48 h. Order also had a negative regression coefficient in IVRun2, but was not significant. Across both IV runs, inoculation order was significant and least squared means, adjusted for the order of inoculation. *In vitro* runs were different ($P < 0.0001$) at 4, 12 and 48 h. Because there was a significant run by treatment interaction at all times of fermentation, gas production was compared across runs and treatments. The interaction was due to detectable differences between Control and CaOH in IVrun1 but not in IVRun2, and to differences in the magnitude of the gas produced by AFEX between runs. Note that the SE of means ($n = 4$) increased to a maximum at the 12 h measurement of IVGP and decreased slightly after that time.

Within both IVRun 1 and 2, AFEX resulted in more gas production ($P<0.001$) at all fermentation times than either Control or CaOH. At fermentation times <12 h there were no differences in gas production ($P<0.05$) between Control and CaOH. At 12 h, Control produced more gas than CaOH in IVRun1 but not IVRun2. At 24 h, Control produced more gas than CaOH in IVRun 2 but not 1. At 48 h, CaOH produced more gas than Control in IVRun 1 and 2.

Theoretically, digestible OM in DM determined *in vivo* should be proportional to *in vitro* gas produced per unit of DM because both represent the portion of DM that is potentially useable by animals. The former indicates the proportion of OM in DM that is digested by animals and the later indicates the proportion of OM in DM that is fermented to gas. The *in vitro* gas production screening tool indicates that the AFEX treatment was superior to Control and CaOH. This observation agrees with the *in vivo* data, which indicated that AFEX provided significantly more digestible OM as a percentage of DM than Control or CaOH when digestibilities were adjusted to 1X maintenance levels of intake.

Table 6. Least squared means for *in vitro* gas production from treatment diets at each time of Fermentation*

	Control		CaOH		AFEX		
Time (hr)	IV Run 1[1]	IV Run 2[1]	IV Run 1	IV Run 2	IV Run 1	IV Run2	SE[2]
2		34.5^{c}		28.2^{b}		36.6^{a}	0.90
4	45.5^{c}	39.0^{d}	45.3^{c}	42.1^{d}	63.7^{a}	58.6^{b}	0.99
8		65.8^{b}		66.3^{b}		101.5^{a}	1.28
12	102.8^{c}	92.3^{d}	97.3^{d}	93.4^{d}	144.3^{a}	134.1^{b}	1.81
24	148.0^{c}	147.1^{c}	147.4^{c}	157.3^{b}	211.5^{a}	201.0^{a}	1.77
48	198.4^{f}	208.8^{d}	203.5^{e}	223.4^{c}	259.7^{b}	264.5^{a}	1.64

* Results are presented as mL of gas/g sample dry matter $^{a-c}$ Means within rows with different letters differ at $P < 0.05$

[1] Least Squared mean results presented for each of the two *in vitro* runs, with data analyzed together

[2] Standard error of the means

Beef cattle trial

At 12 weeks of a 22 week trial the cattle of treatment 1 (AFEX fed) show no significant difference in total weight gain from the control (corn fed) cattle (Figure 17). Table 7 shows detailed information on average daily weight gain, dry matter intake and the ratios of feed/gain and gain/feed. Once again this data shows no significant differences between treatments (AFEX fed and control), and there has been no reported health problems in the test groups.

Figure 17. Average weight gain control vs. Afex

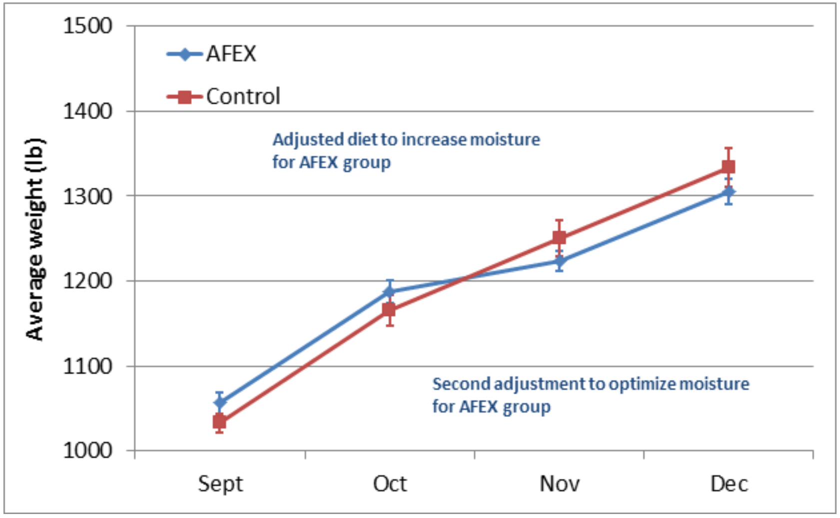


Table 7. Interim Data from Cattle Feeding Trial at Week 12*

Parameter	Control	AFEX
Average Daily Gain (lb)	2.95 ± 0.85	2.93 ± 0.92
Dry Matter Intake (lb/day)	27.95 ± 2.81	27.72 ± 4.28
Feed/Gain	10.09 ± 2.60	10.22 ± 3.09
Gain/Feed	0.10 ± 0.02	0.11 ± 0.03

*** week 12 of 22 weeks**

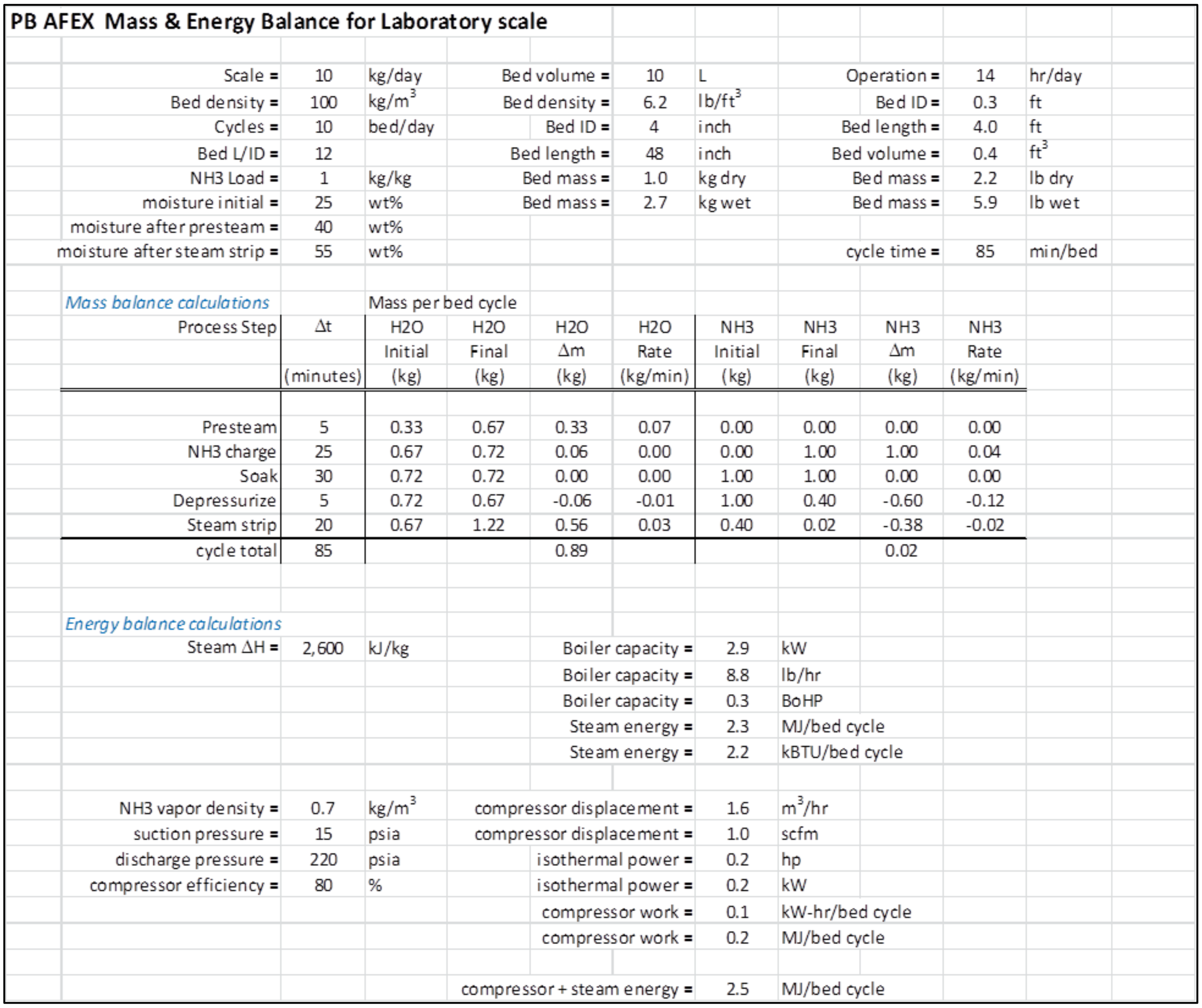
4.3.2.3 Summary

Both *in situ* digestion studies and sheep trials showed that AFEX improves digestibility when compared to control diets and calcium oxide treatment. We have provided strong evidence that AFEX reduces the concentration of neutral detergent fiber and improves the digestibility of the remaining NDF fraction. Archer Daniels Midland has reported that lime treated (calcium oxides/calcium hydroxides) corn stover can be fed to cattle (25% of diet) and achieve comparable weight gain relative to cattle fed a standard diet (**http://origin.adm.com/investors/_layouts/PressReleaseDetail.aspx?ID=292**)**.** Our preliminary data suggests that AFEX is more effective at degrading fiber than calcium oxide. Therefore, we hypothesize that treatment of corn stover with AFEX will allow for greater concentrations of the stover to be utilized in growing and finishing diets without any reduction in animal performance.

A beef cattle finishing trial is currently underway to test this hypothesis. Weight gain data to date shows no significant difference between cattle fed a standard corn-based diet and cattle fed with AFEX-treated corn stover substituted for 30% of the corn. There has been no significant difference in dry matter intake between treatments and the cattle have no reported health problems.

4.4 Pilot-scale AFEX-3 Design

During the current project enough information was generated to begin scale up to pilot scale. Based on the collected data, mass and energy balances (Figure 18) were developed for our lab scale PB AFEX system. During this reporting period preliminary mass and energy balances were also developed for PB AFEX systems for 1 ton-per-day (TPD) (Figure 19) scale. Reactor dimensions and the number of reactors needed to process 1 TPD of corn stover or wheat straw were calculated based on the data [temperature, pressure, biomass bed density (100 kg/m^3), and cycle time (85 min)] collected from our lab scale PB AFEX system. In order to reduce the capital cost, it is essential to increase the throughput rate of the system by increasing the bed density or/and decreasing the cycle time. Based on our current work, there is evidence that corn stover or wheat straw can be processed at a higher bed density and shorter cycle time compared to what was observed in the lab scale system. The preliminary mass and energy balances for a 50 TPD system shown in Figure 8 have been developed assuming bed density of 125 kg/m^3 and cycle time of about 72 min.



PB AFEX Mass & Energy Balance for Laboratory scale

Scale =	10	kg/day	Bed volume =	10	L	Operation =	14	hr/day
Bed density =	100	kg/m^3	Bed density =	6.2	lb/ft^3	Bed ID =	0.3	ft
Cycles =	10	bed/day	Bed ID =	4	inch	Bed length =	4.0	ft
Bed L/ID =	12		Bed length =	48	inch	Bed volume =	0.4	ft^3
NH3 Load =	1	kg/kg	Bed mass =	1.0	kg dry	Bed mass =	2.2	lb dry
moisture initial =	25	wt%	Bed mass =	2.7	kg wet	Bed mass =	5.9	lb wet
moisture after presteam =	40	wt%						
moisture after steam strip =	55	wt%				cycle time =	85	min/bed

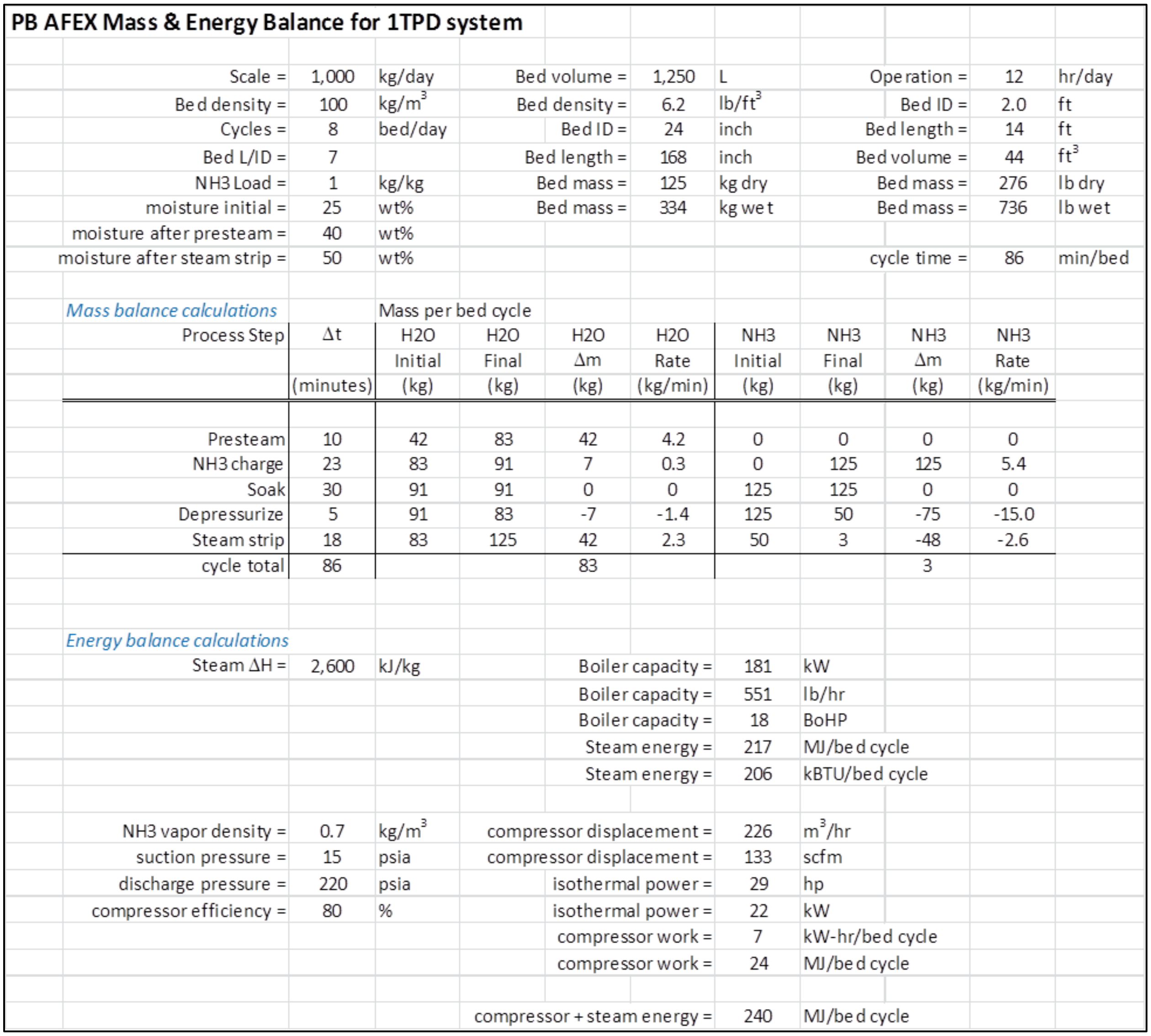
Mass balance calculations — Mass per bed cycle

Process Step	Δt (minutes)	H2O Initial (kg)	H2O Final (kg)	H2O Δm (kg)	H2O Rate (kg/min)	NH3 Initial (kg)	NH3 Final (kg)	NH3 Δm (kg)	NH3 Rate (kg/min)
Presteam	5	0.33	0.67	0.33	0.07	0.00	0.00	0.00	0.00
NH3 charge	25	0.67	0.72	0.06	0.00	0.00	1.00	1.00	0.04
Soak	30	0.72	0.72	0.00	0.00	1.00	1.00	0.00	0.00
Depressurize	5	0.72	0.67	-0.06	-0.01	1.00	0.40	-0.60	-0.12
Steam strip	20	0.67	1.22	0.56	0.03	0.40	0.02	-0.38	-0.02
cycle total	85			0.89				0.02	

Energy balance calculations

Steam ΔH =	2,600	kJ/kg	Boiler capacity =	2.9	kW
			Boiler capacity =	8.8	lb/hr
			Boiler capacity =	0.3	BoHP
			Steam energy =	2.3	MJ/bed cycle
			Steam energy =	2.2	kBTU/bed cycle
NH3 vapor density =	0.7	kg/m^3	compressor displacement =	1.6	m^3/hr
suction pressure =	15	psia	compressor displacement =	1.0	scfm
discharge pressure =	220	psia	isothermal power =	0.2	hp
compressor efficiency =	80	%	isothermal power =	0.2	kW
			compressor work =	0.1	kW-hr/bed cycle
			compressor work =	0.2	MJ/bed cycle
			compressor + steam energy =	2.5	MJ/bed cycle

Figure 18. PB AFEX Mass & Energy Balance for Laboratory Scale



PB AFEX Mass & Energy Balance for 1TPD system

Scale =	1,000	kg/day	Bed volume =	1,250	L	Operation =	12	hr/day
Bed density =	100	kg/m^3	Bed density =	6.2	lb/ft^3	Bed ID =	2.0	ft
Cycles =	8	bed/day	Bed ID =	24	inch	Bed length =	14	ft
Bed L/ID =	7		Bed length =	168	inch	Bed volume =	44	ft^3
NH3 Load =	1	kg/kg	Bed mass =	125	kg dry	Bed mass =	276	lb dry
moisture initial =	25	wt%	Bed mass =	334	kg wet	Bed mass =	736	lb wet
moisture after presteam =	40	wt%						
moisture after steam strip =	50	wt%				cycle time =	86	min/bed

Mass balance calculations

		Mass per bed cycle							
Process Step	Δt (minutes)	H2O Initial (kg)	H2O Final (kg)	H2O Δm (kg)	H2O Rate (kg/min)	NH3 Initial (kg)	NH3 Final (kg)	NH3 Δm (kg)	NH3 Rate (kg/min)
Presteam	10	42	83	42	4.2	0	0	0	0
NH3 charge	23	83	91	7	0.3	0	125	125	5.4
Soak	30	91	91	0	0	125	125	0	0
Depressurize	5	91	83	-7	-1.4	125	50	-75	-15.0
Steam strip	18	83	125	42	2.3	50	3	-48	-2.6
cycle total	86			83				3	

Energy balance calculations

Steam ΔH =	2,600	kJ/kg	Boiler capacity =	181	kW
			Boiler capacity =	551	lb/hr
			Boiler capacity =	18	BoHP
			Steam energy =	217	MJ/bed cycle
			Steam energy =	206	kBTU/bed cycle
NH3 vapor density =	0.7	kg/m^3	compressor displacement =	226	m^3/hr
suction pressure =	15	psia	compressor displacement =	133	scfm
discharge pressure =	220	psia	isothermal power =	29	hp
compressor efficiency =	80	%	isothermal power =	22	kW
			compressor work =	7	kW-hr/bed cycle
			compressor work =	24	MJ/bed cycle
			compressor + steam energy =	240	MJ/bed cycle

Figure 19. PB AFEX Mass & Energy Balance for 1TPD System

In 2011 MBI was awarded a $4.3 million grant from the Department of energy to design, build and operate a 1000 kg (30 kg per bed) capacity AFEX-3 reactor system. Partners in the project are Michigan State University and Idaho National Laboratory. The data collected from the 10 kg prototype system was critical to showing the feasibility of the technology and securing the DOE award. The DOE project overlaps significantly with this North Dakota project, therefore key elements of the DOE project are being included in this report.

4.4.1 Objectives and Scope of Work

The objective of the DOE project is to develop AFEX process improvements that will:

- Lower capital and operating cost by:
    - Altering the AFEX pretreatment system design to exploit the physical and chemical characteristics of the ammonia catalyst and enable:
        - Improved ammonia loading and activity efficiency

- Improved biomass transfer efficiency within the system
- Improved ammonia recovery and reuse efficiency

The scope of work for the DOE project includes the following tasks:

1. Determine the effects of feedstock specifications and reactor design on pretreatment efficacy and ammonia recycle at lab scale
2. Preparation of biomass for pilot scale AFEX-3
3. Design and fabrication of pilot scale AFEX-3
4. Process improvement development at pilot scale
5. Generate and update techno-economic models of the biomass-to-fuel process
6. Determine the quality of pretreated biomass through fermentation use tests
7. Reporting
8. Stage Gate review meetings
9. Final project report

4.4.2 Status

Through a rigorous bid and selection procedure an Engineering, Procurement and Construction (EPC) firm, EPS (South Bend, Indiana), was chosen to facilitate the design and construction of the 1000 kg AFEX-3 system. Mass/energy balances, process flow diagrams, piping and instrumentation diagrams, and detailed mechanical analysis and design were also completed (See Appendix A). MBI and EPS completed the detailed process design for the pilot scale AFEX 3 system, and completed the detailed reactor vessel design. Major equipment, including the compressor, scrubber, heat exchangers, and tanks, was specified and costs determined. The required modifications for the room where the AFEX-3 pilot scale is installed, included safety systems were finalized and completed and all of the equipment has been installed (Figure 20). Safety review and evaluations were also completed.

The 1 TPD system is being used to provide AFEX pellets for animal feeding trials and reactor systems continue to be refined to meet performance parameters regarding treatment efficiency, throughput and ammonia recovery. In July 2013 personnel from the National Renewable Energy Laboratory (NREL) conducted a technology validation at the bequest of the Department of Energy. This included witnessing full operation of the AFEX-3 1 TPD system and all analytical methods and analyses, as well as reviewing our techno-economic analysis assumptions and calculations. NREL approved and validated all data related to the project and approved a third year of the project to complete operational tasks to meet final performance targets. Reports to the US DOE detailing the fabrication, installation and operation of the 1 TPD AFEX-3 system are attached in Appendix B.

Figure 20. Pilot plant AFEX 3 system located at MBI

4.5 Proforma for regional biomass processing centers using the AFEX-3 reactor

4.5.1 *Process*

The AFEX depot is designed to have a 110 US dry ton biomass/day capacity, running 24 hours per day and 350 days per year. The depot is scalable to a 220 dry ton biomass/ day depot, which is also modeled. Biomass is collected throughout the surrounding area and brought to the depot in bales. Bales are transported to the depot and removed using a bale handler. Because previous research has suggested lack of willingness of producers to store biomass, storage is assumed to be on-sight (Leistritz et al. 2009.). Bales are shredded and milled to 1" particle size prior to entering the AFEX process. The milled biomass is packed into AFEX reactors at a bulk density of 100 kg dry weight per m^3 and a moisture content of ~20%. AFEX is performed in stainless steel vertical pressure vessels that are 5 ft in diameter and 35 ft tall with a single quick-opening hatch at the top of the reactor. After treatment, the biomass exits at ~40% moisture. It is dried to <20% in a triple pass rotary drum dryer, which also removes any residual ammonia. The dried, treated biomass is milled further to 1/4 inch particle size before being pelletized and cooled. The heat of pelletization brings the final moisture to 15%, which is low enough to be safely stored. The pellets can then be stored, metered out, and shipped in a manner similar to corn grain.

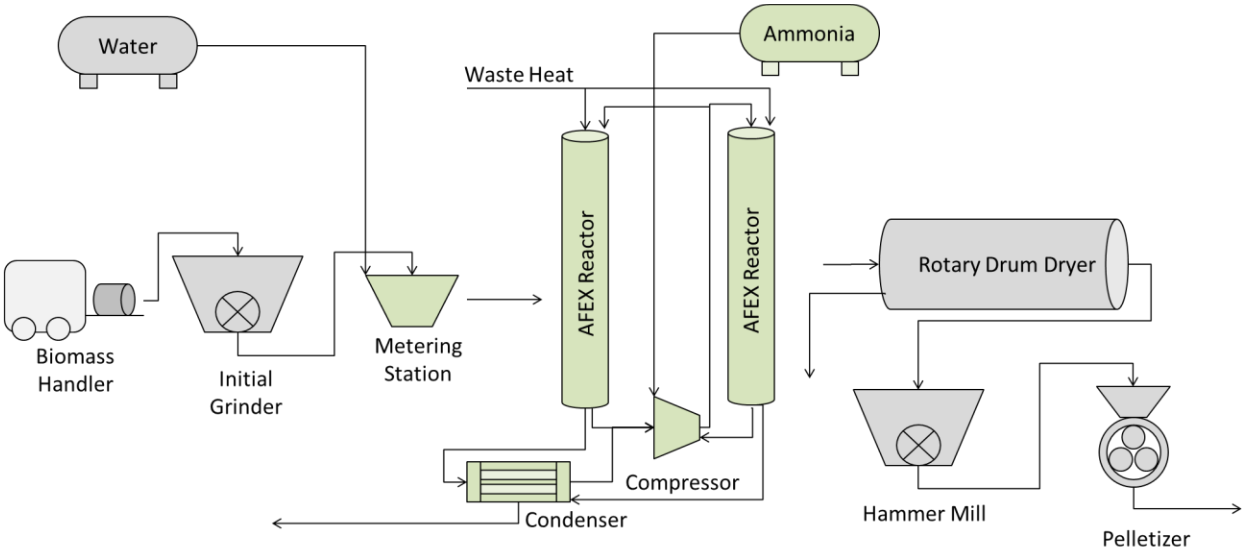


Figure 21. Schematic of an AFEX processing depot. Green components are the core AFEX components

4.5.2 Capital Investment

List of equipment

Temporary bale storage – Bales are stored on gravel on flat land. Bales are covered in tarps to prevent rain or snow damage. We assume the depot is a mix of corn stover and wheat straw, and that biomass must be stored year-round. The storage area was modeled as blocks of 120 tons of biomass separated by 16 ft alleys, and used the IBSAL model to estimate the cost of gravel and tarps. Approximately 500,000 square feet (11.5 acres) are needed to store the biomass at a cost of $1.36/ft^2.

Telescopic bale loader/unloader – This is standard equipment for dealing with agricultural biomass. Based on our modeling, three loaders are necessary to unload biomass bales arriving from trucks and place them in the grinder or storage during harvest times, while one loader is required to remove bales from storage and place in grinder for the rest of the year. Cost of the bale loader was estimated from the IBSAL model.

Initial stage grinder – This can be either a top-loading tub grinder or an enclosed horizontal loader. The horizontal model is more expensive but would reduce the loss of fines. Throughput will be relatively fast due to the large particle size allowance (1”). The price is based on a quote. Installation cost was assumed to be relatively low due to the fact that these are generally stand-alone pieces of equipment.

Metering station – For this model, it is assumed that the biomass is packed into baskets and that the baskets are loaded into the reactor. This station will load the biomass into the baskets at its native bulk density (~60 kg/m^3) and then compress it to the desired bulk density, likely with a pneumatic piston. Price is estimated based on a ribbon blender as the metering station and an internal estimate for the piston.

Ammonia hold tank – This tank is standard equipment and designed to hold 24 metric tonnes of ammonia. This would supply an estimated 12 days of processing. The price was obtained based on a similar tank's cost quoted for NREL's cellulosic ethanol model (Humbird et al., 2011).

AFEX reactor – Reactors work in pairs and can process ~25 metric tons per day. Thus, 4 reactors are required for the full depot. The price is estimated based on the purchased cost of reactors for MBI's pilot scale system. Installation cost is estimated based off other similar equipment. Total residence time in each reactor is 110 minutes per batch.

Ammonia compressor – Because the compressor is running for less than 1/4 of the total residence time for each reactor, then it is believed that 1 compressor can service all four reactors. The compressor is capable of handling pressures from 0 to 300 psi and is compatible with ammonia. The purchase price is estimated based on the purchased cost for MBI's pilot scale system and scaled to the appropriate size.

Water condenser – This condenser removes residual water from the ammonia stream exiting an AFEX reactor. Removing water protects the compressor from excess wear, extending its lifetime. This is a standard piece of equipment, and priced based on the estimated cooling duty required for the process.

Triple pass dryer – Triple pass rotary drum dryers are designed for non-homogenous material to ensure even drying. Given the range of particle sizes present, this was deemed the best dryer available. The dryer is a standard piece of equipment and both purchase and installation costs were provided by a manufacturer's quote.

Hammer mill – The presence of this hammer mill is to reduce the wear and improve throughput in the pelletizer. Because the biomass is treated and is already reduced in size, a relatively small mill is needed, as the throughput should be high. The price was obtained from the IBSAL model.

Pelletizer – A conventional ring-die pelletizer can be used to pelletize AFEX treated biomass. Based on MBI's experience with a flat-die pelletizer, the throughput should be much faster with AFEX material compared to untreated material due to the presence of lignin on the surface of the AFEX treated biomass. Thus, a smaller pelletizer may be used relative to what is shown here. The price was obtained from the IBSAL model.

Pellet storage – A conventional corn grain storage bin was modeled here. Pellet storage was assumed to be for a maximum of 10 days. The price of corn grain storage bin was estimated from literature.

Boiler – AFEX requires low pressure (<65 psi) steam. Natural gas will be used as the energy source. This is a standard piece of equipment and the price estimated from the maximum amount of steam needed at one time.

Minor equipment – This catchall category includes conveying systems, pellet coolers, and any other equipment that may be necessary in the process. It was estimated to be 5% of the total cost.

Total equipment cost – The cost of the AFEX system dominates the total installed cost of the depot, with a total cost of $2.7 million for the reactors and an additional $1.4 million for the compressor. The dryer is also a significant cost in the system at nearly $1 million. If the AFEX biomass is to be used locally (in a co-located beef farm, for example), then this dryer can be eliminated, as can the pelletizer. Other biomass handling equipment is a relatively small contribution to the overall cost.

Indirect costs

Indirect capital expenditures are estimated to be 30% of the installed capital cost. These expenditures include land purchase and development, legal permitting and engineering design, office construction, and contingencies. This model assumes an Nth plant situated on a brownfield site in a rural location. Thus, some of these costs are expected to be low (for example, it is expected that the engineering of the equipment is already complete, and the only engineering design is in situating the depot to the particular location). In addition, the site is assumed to be co-located with other rural industries (e.g., a grain elevator) in order to share resources such as utilities and office space.

Table 8. Summary of capital costs in an AFEX depot (110 tons per day)

Equipment Name	Purchasing Cost (thousands of dollars)	Installation Cost (thousands of dollars)	Total Cost (thousands of dollars)
Bale Handler	345	0	345
Bale storage	689	0	689
Initial Stage Grinder	40	8	48
Ammonia hold tank	45	45	90
Biomass metering station	150	210	360
AFEX Reactors	1,120	1,568	2,688
Compressor	600	840	1,440
Condenser	75	75	150
Dryer	450	450	900
Hammer mill	59	12	71
Pelletizer	135	81	216
Pellet silo	35	35	70
Boiler	45	36	81
Minor equipment	150	167	317
Total Equipment Cost	3,938	35,273,527	7,465
Indirect Costs (30% of total installed costs)			2,240
Total Capital Investment			9,705

Table 9. Summary of Capital Costs in an AFEX depot (220 tons per day)

Equipment Name	Purchasing Cost (thousands of dollars)	Installation Cost (thousands of dollars)	Total Cost (thousands of dollars)
Bale Handler	690	0	690
Bale storage	1,378	0	1,378
Initial Stage Grinder	60	12	72
Ammonia hold tank	68	68	136
Biomass metering station	227	319	546
AFEX Reactors	2,240	3,316	5,376
Compressor	1,200	1,680	2,880
Condenser	113	113	226
Dryer	682	682	1,364
Hammer mill	89	18	107
Pelletizer	204	123	327
Pellet silo	70	70	140
Boiler	68	55	123
Minor equipment	319	256	575
Total Equipment Cost	7,408	6,712	13,940
Indirect Costs (30% of total installed costs)			4,530
Total Capital Investment			18,470

4.5.3 Operating Costs

Raw material

The raw material can be any member of the grass family, including corn stover, wheat straw, barley straw, or dedicated energy grasses. Approximately 1 ton of AFEX pellets are obtained per ton of entering biomass. Thus, no losses are modeled through the process from the grinder to pellet storage. However, 5 percent storage loses were modeled to account for spoilage. Corn stover acquisition cost was estimated to be just over $67 per ton ($67.03) and wheat straw cost was estimated to be just over $58 per ton ($58.39). A breakdown of acquisition costs is detailed later in the report in the section discussing biomass availability. Total biomass cost assuming 65 percent corn stover and 35 percent wheat straw was $2.5 million for a 110 ton per day facility or $4.9 million for a 220 ton per day facility.

Utilities

Although most of the ammonia is recycled, a portion of the ammonia reacts with the biomass and must be replaced. In addition, not all ammonia will be removed in the process, although it is designed to remove ~99% of the non-reacted ammonia. Ammonia is modeled as 3 tons consumed per 100 tons biomass treated at $600/US ton cost.

Electricity is required for the mills, the pelletizer, the dryer, the boiler, and the compressor. Approximately 73 kWh are required per US dry ton of biomass treated. An industrial electricity rate is used for this depot, as the depot will run 24 hours per day and thus consume off-peak electricity.

Natural gas is required for both the boiler as well as the dryer. Approximately 2.3 MMBTU natural gas is needed per ton of biomass for steam generation, and an additional 1.45 MMBTU needed to dry the biomass post-AFEX.

Approximately 0.85 tons of water are required per ton of AFEX treated biomass. This water is removed in the rotary drum dryer and assumed to be vented to the atmosphere. Thus, it must be replaced. Water cost were estimated to be $5.22 per 1,000 gallons or $1.15 per ton.

Fixed costs

The entire depot process is automated once biomass is loaded into the initial tub grinder. Thus, a low number of employees are needed. In total, we expect 3 people per shift can monitor the entire process and control it if needed. Salary between the three personnel is varied based on skill level and responsibility; one person per shift will be the supervisor and two will be expected to be able to perform routine maintenance. In addition, an additional laborer is present during normal business hours to assist in loading and unloading biomass. Additional season workforce to handle biomass delivery estimates to be equal to 1 FTE for a 110 ton per day depot and 2FTEs for a 220 ton per day depot. A single office administration person is also present. Benefits and overhead is estimated to be 30% of the total salary.

Table 10. Summary of labor requirements in an AFEX depot (110 ton per day)

Position	employees	Salary /employee ($/yr)	Benefits/ overhead	Total Cost
Office administration	1	$40,000	$12,000	$52,000
Shift Supervisor	4	$38,220	$11,466	$198,744
Control operator	4	$34,944	$10,483	$181,708
Laborer	4	$26,208	$7,862	$136,280
Bale handler	1	$31,200	$9,360	$40,560
Seasonal bale handler (4 at .25 FTE)	1	$23,500	$3,000	$26,500
Total	14			$635,792

Table 11. Summary of labor requirements in an AFEX depot (220 ton per day)

Position	employees	Salary per employee ($/yr)	Benefits/ overhead	Total Cost
Office admin	1	$40,000	$12,000	$52,000
Shift Supervisor	4	$38,220	$11,466	$198,744
Control operator	4	$34,944	$10,483	$181,708
Laborer	4	$26,208	$7,862	$136,280
Bale handler	2	$31,200	$9,360	$81,1200
Seasonal bale handler (4 at .25 FTE)	2	$23,500	$3,000	$53,000
Total	16			702,852

Maintenance and insurance is estimated to be 2.3% of the total installed cost of the depot. Maintenance on the AFEX reactors are expected to be low due to their simple design. Likewise, maintenance on the pelletizer is expected to be lower than other pelletizers due to the ease of pelletizing AFEX treated material.

Total cash costs

Total cash cost is $4.7 million per year, or $122 per US dry ton inclusive of biomass price. This is equivalent to corn grain at $2.90 per bushel. Excluding the cost of biomass, the cash cost of AFEX treatment is $54 per US dry ton. Capital recovery charge is estimated by averaging the capital cost over the lifetime of the plant (20 years) and including a 7% interest rate. This equates to an additional $21/US ton, or $804 thousand per year. Thus, the breakeven price for the depot is $146 per US dry ton, or $3.50/bu corn equivalent.

Table 12. Final cost summary of an AFEX depot (110 ton per day)

Raw Materials	$/US ton	Thousand $/yr
Biomass, Corn Stover	$66.30	$1,761
Biomass, Wheat Straw	$57.66	$826
Utilities		
Ammonia	$18.00	$693
Electricity	$5.22	$201
Natural Gas	$13.8	$531
Water	$1.06	$41
Fixed Costs		
Labor	$16.50	$636
Maintenance + Insurance	$3.89	$150
Total Cash Costs	$122.50	$4,839
Capital Recovery Charge	$23.72	$916
Total Cost	$146.20	$5,755

Table 13. Final cost summary of an AFEX depot (220 tons per day)

Raw Materials	$/US ton	Thousand $/yr
Biomass, Corn Stover	$66.30	$3,522
Biomass, Wheat Straw	$57.66	$1,652
Utilities		
Ammonia	$18.00	$1,386
Electricity	$5.22	$402
Natural Gas	$13.8	$1,063
Water	$1.06	$82
Fixed Costs		
Labor	$9.13	$703
Maintenance + Insurance	$3.28	$253
Total Cash Costs	$114.50	$8,921
Capital Recovery Charge	$22.58	$1,743
Total Cost	$137.08	$10,664

4.5.4 Feedstock Production

While the feedstock requirements for a single AFEX depot are much less than estimates of feedstock needs for a commercial scale biorefinery (Lestritz et al. 2006), an examination of available feedstock and acquisition costs in North Dakota is warranted. Further an assessment of feedstock can illustrate the theoretical maximum raw biomass potentially available for AFEX pretreated biomass for use as animal feed or as a feedstock for other technologies or processes such as hydrolysis, or conversion into other renewable fuels or chemicals. Total available biomass and the maximum number of AFEX pretreatment depots that could be supported by available biomass will be estimated at the State Crop Reporting District level (Figure 25)**.**

4.5.4.1 Wheat Straw

North Dakota harvested acres of all wheat has ranged from 6,590,000 acres in 2011 to 12,515,000 in 1996 (Figure 22). Harvested acres has varied during the 1980-2012 period, but has typically remained above 8 million acres with the exception of a few years. Relatively higher commodity prices for soybeans and corn and new varieties that have expanded growing regions have drawn acres away from wheat and into corn and soybean production in recent years. Wheat yields have generally increased in the last two decades, although there is significant year-to-year variability (Figure 23). Bushels harvested have only averaged over 40 bushels per acre 4 times since 1980, however in three of the five last years, yields have averaged over forty bushels per acre(46.0, 43.7 and 43.0 bushels per acre in 2009, 2012, and 2010, respectfully) (Figure 23).

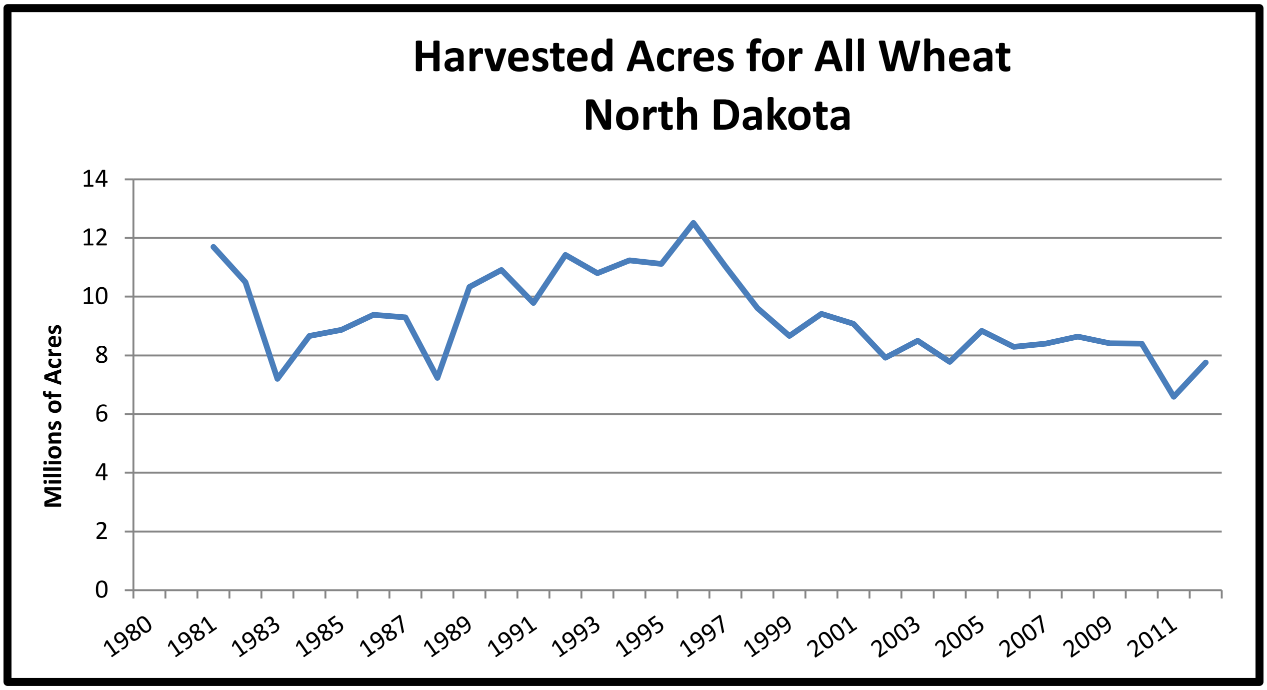


Figure 22. Harvested Acres for All Wheat, North Dakota, 1980-2012

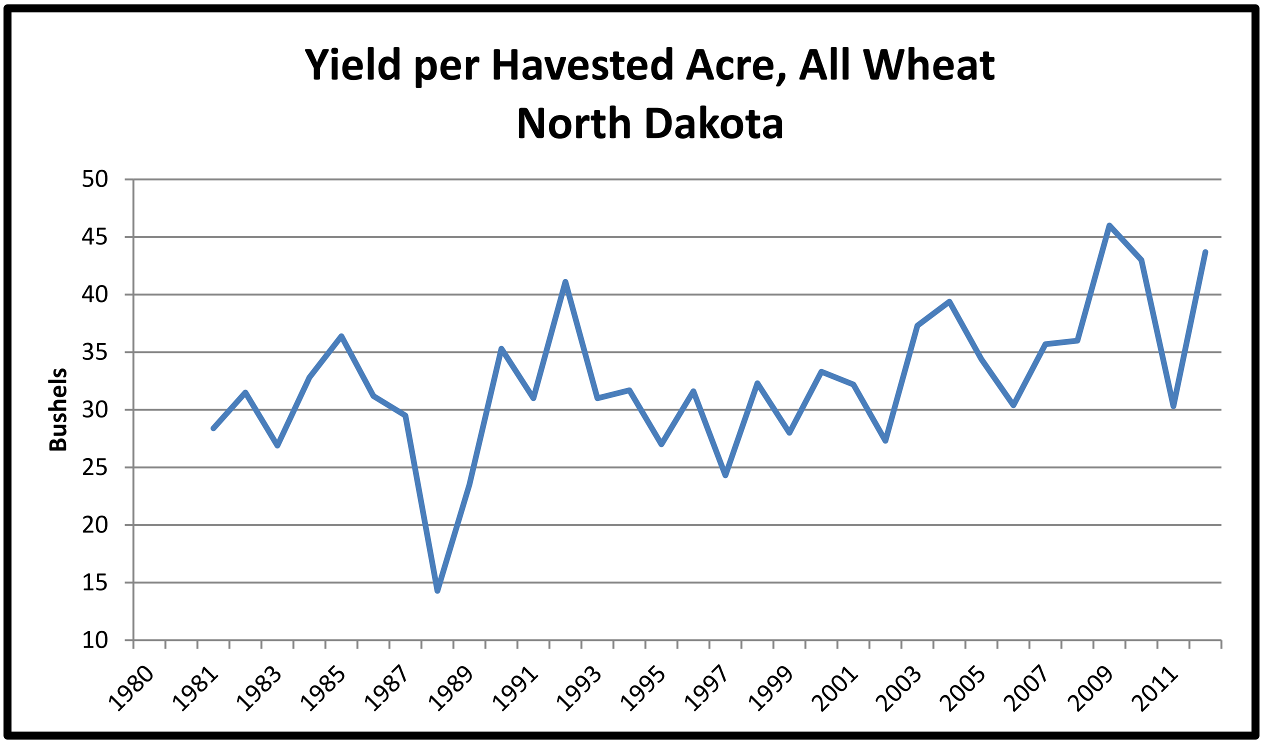


Figure 23. Average Yeild per Harvested Acre, All Wheat, North Dakota, 1980-2012

Wheat straw produced for a given wheat yield can be estimated using a Harvest Index formula (Ottman et al. 2000). The formula is as follows:

$$\text{Harvest Index} = \frac{\text{dry grain weight}}{\text{total plant dry weight}}$$

Average Harvest Index for North Dakota wheat is 0.38 (Ransom 2004; Chen et al. 2008). In 2012, average wheat yield per acre was 43.7 bushels. That yield would produce 3,722 pounds of dry straw per acre would . The calculation is as follows:

$$0.38 = \frac{\text{dry grain weight}}{\text{total plant dry weight}}$$

43.7 bu/acre = 2,622 pounds of wheat at 13 percent moisture, adjusted to 0 percent moisture(2,622 x .87 = 2,281.14)

$$0.38 = \frac{2{,}281.14}{2{,}281.14 + x \text{ (where x is the weight of the wheat straw)}}$$

$$2{,}281.14 = 0.38\,(2{,}281.14) + 0.38\,(x)$$

$$2{,}281.14 = 866.83 + 0.38\,(x)$$

$$1{,}414.31 = 0.38(x)$$

$$x = 3{,}722 \text{ pounds of straw per acre}$$

Acres harvested, average straw yield per acre, and total straw production for the period 1980-2012 in North Dakota are detailed in Table 12.

Table 14. Wheat harvested, yield and straw production, North Dakota, 1980 to 2012.

Year	Area Harvested	Yield Per Acre	Straw Produced Per Acre	Total Straw Production[1]
	----acres-----	---bushels---	---Pounds---	----tons----
1980	9,620,000	18.7	1,592.7	7,660,644.0
1981	11,690,000	28.4	2,418.8	14,137,787.6
1982	10,490,000	31.5	2,682.8	14,071,313.6
1983	7,205,000	26.9	2,291.0	8,253,437.5
1984	8,660,000	32.8	2,793.5	12,095,959.8
1985	8,870,000	36.4	3,100.1	13,749,078.9
1986	9,380,000	31.2	2,657.3	12,462,524.7
1987	9,300,000	29.5	2,512.5	11,682,978.2
1988	7,230,000	14.3	1,217.9	4,402,738.9
1989	10,330,000	23.5	2,001.5	10,337,530.0
1990	10,910,000	35.3	3,006.5	16,400,158.9
1991	9,790,000	31.0	2,640.2	12,923,882.1
1992	11,420,000	41.1	3,500.4	19,987,410.2
1993	10,800,000	31.0	2,640.2	14,257,193.7
1994	11,238,000	31.7	2,699.8	15,170,395.1
1995	11,114,000	27.0	2,299.6	12,778,584.7
1996	12,515,000	31.6	2,691.3	16,840,948.1
1997	11,025,000	24.3	2,069.6	11,408,629.4
1998	9,610,000	32.3	2,750.9	13,218,266.7
1999	8,657,000	28.0	2,384.7	10,322,242.3
2000	9,413,000	33.3	2,836.1	13,348,144.3
2001	9,080,000	32.2	2,742.4	12,450,601.1
2002	7,915,000	27.3	2,325.1	9,201,574.9
2003	8,500,000	37.3	3,176.8	13,501,324.0
2004	7,775,000	39.4	3,355.6	13,045,034.1
2005	8,835,000	34.4	2,929.8	12,942,363.6
2006	8,290,000	30.4	2,589.1	10,731,902.4
2007	8,405,000	35.7	3,040.5	12,777,754.3
2008	8,640,000	36.0	3,066.1	13,245,392.8
2009	8,415,000	46.0	3,917.7	16,483,922.1
2010	8,400,000	43.0	3,662.2	15,381,416.8
2011	6,590,000	30.3	2,580.6	8,503,087.4
2012	7,760,000	43.7	3,721.9	14,440,816.8

[1] Wheat acres harvested multiplied by the pounds of straw produced per acre. Dry weight basis. Source: National Agricultural Statistics Service (2005); (2006); (2007); (2008); (2009); (2010); (2011); (2012); (2013a).

Yield increases over time have offset the potential decline in wheat straw production due to changing cropping pattern. North Dakota's nearly 8 million acres of wheat harvested annually in recent years is down from peak acreage of 10-12 million acres in the 1990s, but still represents a significant portion of crop acres in the state. The shift in production from wheat to corn has not significantly changed the amount of wheat biomass available. North Dakota's nearly 8 million acres of wheat harvested annually in recent years is down from peak acreage of 10-12 million acres in the 1990s, but still represents a significant portion of crop acres in the state.

North Dakota crop production data are collected at the county level by the National Agricultural Statistic Service (NASS) and are grouped into nine Crop Reporting Districts (Figure 24). These districts tend to have counties that grow similar crops, have similar weather patterns, and similar geographic characteristics. In years where an insufficient number of responses to the crop production surveys from a county are collected, county data is not released to avoid potential disclosure issues. This results in missing county data for some years. Aggregating results to Crop Reporting Districts eliminate potential disclosure issues and provides a better indicator of regional biomass availability.

Estimated straw production for each of North Dakota's nine Crop Reporting Districts is presented in (Tables 15-22). Straw production per acre for each of the respective Crop Reporting Districts was calculated using the Harvest Index formula previously discussed. Estimates of straw production do not take into consideration harvest limitations. Lundstrom (1994) estimate 43 percent of total straw production can be recovered through baling. Recoverable biomass will be examined later in the report.

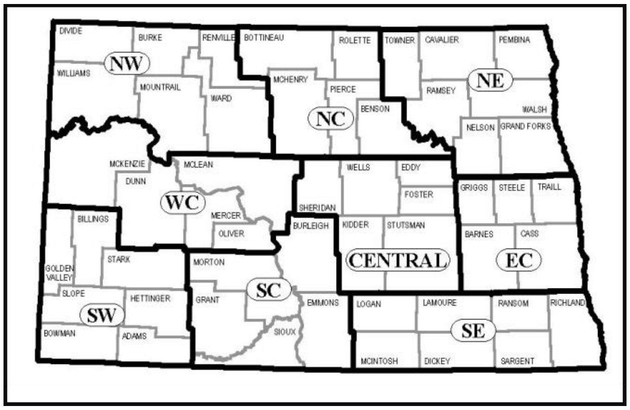


Figure 24. NASS Crop Reporting Districts, North Dakota

Table 15. Estimated Per Acre and Total Wheat Straw Production, All Wheat, Using the Harvest Index Formula, Based on NASS Acreages and Yields, Central Crop Reporting District, North Dakota, 1980-2012

Year	Acres Harvested	Yield Per Acre	Straw Production per Acre	Total Straw Production[1]
	----acres----	----bushels----	----pounds----	----tons----
1980	1,030,450	18.3	1,559	803,021
1981	1,268,500	29.4	2,504	1,588,131
1982	1,060,500	31.3	2,666	1,413,525
1983	748,500	25.7	2,189	819,169
1984	922,500	32	2,725	1,257,086
1985	969,000	32.5	2,768	1,341,083
1986	1,038,000	29.4	2,504	1,299,551
1987	982,500	28.6	2,436	1,196,595
1988	712,200	11.7	997	354,843
1989	1,067,900	18	1,533	818,562
1990	1,134,000	40.6	3,458	1,960,594
1991	1,051,900	30.6	2,606	1,370,707
1992	1,202,000	37.1	3,160	1,899,009
1993	1,127,400	31	2,640	1,488,293
1994	1,183,900	31.4	2,674	1,583,045
1995	1,118,900	25.4	2,163	1,210,246
1996	1,287,100	30.8	2,623	1,688,152
1997	1,058,200	22.7	1,933	1,022,921
1998	827,700	28.6	2,436	1,008,063
1999	814,900	25.5	2,172	884,898
2000	744,300	32	2,725	1,014,254
2001	834,500	28.2	2,402	1,002,130
2002	674,300	23.9	2,036	686,277
2003	668,800	42	3,577	1,196,173
2004	622,100	42.9	3,654	1,136,491
2005	698,500	38.1	3,245	1,133,287
2006	621,800	33.6	2,862	889,690
2007	638,400	39.8	3,390	1,081,993
2008	681,000	45	3,833	1,304,993
2009	651,000	47.1	4,011	1,305,721
2010	630,730	47.1	4,011	1,265,066
2011	609,600	29	2,470	752,821
2012	466,100	46.8	3,986	928,910

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable. Source: NASS

Table 16. Estimated Per Acre and Total Wheat Straw Production, All Wheat, Using the Harvest Index Formula, Based on NASS Acreages and Yields, East Central Crop Reporting District, North Dakota, 1980-2012

Year	Acres Harvested	Yield Per Acre	Straw Production per Acre	Total Straw Production[1]
	----acres----	----bushels----	----pounds----	----tons----
1980	1,193,500	22.5	1,916	1,143,546
1981	1,225,500	34.2	2,913	1,784,794
1982	1,132,000	38.4	3,271	1,851,085
1983	765,000	31.2	2,657	1,016,400
1984	946,900	44.5	3,790	1,794,373
1985	942,000	46.9	3,994	1,881,362
1986	971,000	33.4	2,845	1,381,066
1987	973,200	37.5	3,194	1,554,111
1988	926,300	20.5	1,746	808,638
1989	1,197,000	29.6	2,521	1,508,810
1990	1,296,000	49.1	4,182	2,709,787
1991	1,073,700	38.5	3,279	1,760,323
1992	1,327,500	48.1	4,097	2,719,119
1993	1,239,600	29.4	2,504	1,551,949
1994	1,199,500	31.7	2,700	1,619,228
1995	1,205,200	28.8	2,453	1,478,088
1996	1,330,100	39.6	3,373	2,242,994
1997	1,190,700	27.9	2,376	1,414,670
1998	1,007,000	38.1	3,245	1,633,816
1999	1,038,700	32.5	2,768	1,437,547
2000	950,600	42.3	3,603	1,712,327
2001	939,300	41.2	3,509	1,647,973
2002	809,700	35.2	2,998	1,213,711
2003	745,700	52.9	4,505	1,679,842
2004	648,800	53.6	4,565	1,480,895
2005	776,700	38.9	3,313	1,286,624
2006	n/a	n/a	n/a	n/a
2007	549,600	42.5	3,620	994,682
2008	n/a	n/a	n/a	n/a
2009	455,000	53.8	4,582	1,042,419
2010	482,800	56.6	4,821	1,163,677
2011	430,700	31.8	2,708	583,244
2012	353,600	56.1	4,778	844,741

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable. Source: NASS

Table 17. Estimated Per Acre and Total Wheat Straw Production, All Wheat, Using the Harvest Index Formula, Based on NASS Acreages and Yields, Central Crop Reporting District, North Dakota, 1980-2012

Year	Acres Harvested	Yield Per Acre	Straw Production per Acre	Total Straw Production[1]
	----acres----	----bushels----	----pounds----	----tons----
1980	1,030,450	18.3	1,559	803,021
1981	1,268,500	29.4	2,504	1,588,131
1982	1,060,500	31.3	2,666	1,413,525
1983	748,500	25.7	2,189	819,169
1984	922,500	32	2,725	1,257,086
1985	969,000	32.5	2,768	1,341,083
1986	1,038,000	29.4	2,504	1,299,551
1987	982,500	28.6	2,436	1,196,595
1988	712,200	11.7	997	354,843
1989	1,067,900	18	1,533	818,562
1990	1,134,000	40.6	3,458	1,960,594
1991	1,051,900	30.6	2,606	1,370,707
1992	1,202,000	37.1	3,160	1,899,009
1993	1,127,400	31	2,640	1,488,293
1994	1,183,900	31.4	2,674	1,583,045
1995	1,118,900	25.4	2,163	1,210,246
1996	1,287,100	30.8	2,623	1,688,152
1997	1,058,200	22.7	1,933	1,022,921
1998	827,700	28.6	2,436	1,008,063
1999	814,900	25.5	2,172	884,898
2000	744,300	32	2,725	1,014,254
2001	834,500	28.2	2,402	1,002,130
2002	674,300	23.9	2,036	686,277
2003	668,800	42	3,577	1,196,173
2004	622,100	42.9	3,654	1,136,491
2005	698,500	38.1	3,245	1,133,287
2006	621,800	33.6	2,862	889,690
2007	638,400	39.8	3,390	1,081,993
2008	681,000	45	3,833	1,304,993
2009	651,000	47.1	4,011	1,305,721
2010	630,730	47.1	4,011	1,265,066
2011	609,600	29	2,470	752,821
2012	466,100	46.8	3,986	928,910

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable. Source: NASS

Table 18. Estimated Per Acre and Total Wheat Straw Production, All Wheat, Using the Harvest Index Formula, Based on NASS Acreages and Yields, Northeast Crop Reporting District, North Dakota, 1980-2012

Year	Acres Harvested	Yield Per Acre	Straw Production per Acre	Total Straw Production[1]
	----acres----	----bushels----	----pounds----	----tons----
1980	1,924,500	21.8	1,857	1,786,582
1981	2,149,500	33.9	2,887	3,103,028
1982	2,049,000	37.2	3,168	3,245,888
1983	1,336,000	31.3	2,666	1,780,735
1984	1,600,800	42	3,577	2,863,090
1985	1,678,000	47.5	4,046	3,394,175
1986	1,768,000	34.6	2,947	2,604,995
1987	1,770,400	38.2	3,253	2,879,940
1988	1,658,800	19.7	1,678	1,391,582
1989	2,078,800	31.8	2,708	2,815,065
1990	2,229,000	38.9	3,313	3,692,396
1991	1,986,900	35.5	3,024	3,003,675
1992	2,272,500	49.3	4,199	4,770,890
1993	1,874,200	25.4	2,163	2,027,208
1994	2,184,300	28.3	2,410	2,632,372
1995	2,075,400	26.8	2,283	2,368,565
1996	2,068,600	33.3	2,836	2,933,387
1997	1,804,400	26.7	2,274	2,051,600
1998	1,519,900	36.1	3,075	2,336,527
1999	1,574,000	32.2	2,742	2,158,287
2000	1,765,700	36.1	3,075	2,714,393
2001	1,506,500	32.1	2,734	2,059,315
2002	1,481,100	34.6	2,947	2,182,273
2003	1,476,500	47	4,003	2,955,153
2004	1,364,300	49	4,173	2,846,784
2005	1,498,900	33.5	2,853	2,138,287
2006	1,497,000	39.2	3,339	2,498,944
2007	1,434,300	43.3	3,688	2,644,701
2008	1,592,800	51	4,344	3,459,235
2009	1,329,000	50	4,258	2,829,721
2010	1,484,200	49.9	4,250	3,153,854
2011	1,331,100	40.6	3,458	2,301,364
2012	1,288,300	53.4	4,548	2,929,590

[1] Dry weight basis. Estimates represent total straw production, only which a portion of which is recoverable. Source: NASS

Table 19. Estimated Per Acre and Total Wheat Straw Production, All Wheat, Using the Harvest Index Formula, Based on NASS Acreages and Yields, Northwest Crop Reporting District, North Dakota, 1980-2012

Year	Acres Harvested	Yield Per Acre	Straw Production per Acre	Total Straw Production[1]
	----acres----	----bushels----	----pounds----	----tons----
1980	1,584,500	19.4	1,652	1,309,009
1981	1,769,500	28.2	2,402	2,124,948
1982	1,589,000	30.6	2,606	2,070,589
1983	1,228,500	25.6	2,180	1,339,256
1984	1,337,100	22.9	1,950	1,303,911
1985	1,293,000	29.5	2,513	1,624,311
1986	1,445,000	35.2	2,998	2,166,003
1987	1,379,700	23	1,959	1,351,329
1988	1,267,100	12.2	1,039	658,293
1989	1,636,700	17.9	1,525	1,247,587
1990	1,676,500	31.3	2,666	2,234,583
1991	1,567,900	30.1	2,564	2,009,710
1992	1,781,000	38.7	3,296	2,935,104
1993	1,806,600	36.6	3,117	2,815,734
1994	1,843,300	35	2,981	2,747,342
1995	1,920,500	28.6	2,436	2,338,993
1996	2,204,400	29.2	2,487	2,741,081
1997	2,044,900	21.7	1,848	1,889,646
1998	1,984,700	30.7	2,615	2,594,668
1999	1,606,500	27.5	2,342	1,881,317
2000	1,904,900	29.3	2,495	2,376,777
2001	1,828,800	25.4	2,163	1,978,101
2002	1,650,400	26.5	2,257	1,862,446
2003	1,741,700	28.7	2,444	2,128,648
2004	1,372,000	35.6	3,032	2,079,949
2005	1,717,000	35.5	3,024	2,595,657
2006	1,736,500	27.4	2,334	2,026,161
2007	1,788,000	32.4	2,760	2,466,954
2008	1,988,000	31	2,640	2,624,380
2009	1,879,000	40	3,407	3,200,629
2010	1,780,300	38.3	3,262	2,903,625
2011	778,400	27.5	2,342	911,558
2012	1,843,000	38.3	3,262	3,168,985

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable. Source: NASS

Table 20. Estimated Per Acre and Total Wheat Straw Production, All Wheat, Using the Harvest Index Formula, Based on NASS Acreages and Yields, South Central Crop Reporting District, North Dakota, 1980-2012

Year	Acres Harvested	Yield Per Acre	Straw Production per Acre	Total Straw Production
	----acres----	----bushels----	----pounds----	----tons----
1980	401,050	10.8	920	184,447
1981	787,500	22	1,874	737,772
1982	673,000	24	2,044	687,820
1983	445,500	22.1	1,882	419,265
1984	585,000	26.7	2,274	665,144
1985	618,000	27.4	2,334	721,087
1986	610,000	24.7	2,104	641,616
1987	570,500	25.1	2,138	609,787
1988	224,100	7	596	66,802
1989	505,500	12	1,022	258,316
1990	512,000	18.2	1,550	396,817
1991	612,800	22.1	1,882	576,713
1992	732,000	32.6	2,777	1,016,196
1993	725,800	28.2	2,402	871,595
1994	722,400	28.2	2,402	867,512
1995	751,000	22.3	1,899	713,171
1996	867,700	26.6	2,266	982,879
1997	785,200	20.3	1,729	678,774
1998	688,500	28.2	2,402	826,802
1999	590,200	21.8	1,857	547,904
2000	627,300	33.3	2,836	889,545
2001	604,000	32.5	2,768	835,928
2002	355,500	14.8	1,261	224,053
2003	600,200	26.8	2,283	684,982
2004	644,900	29.2	2,487	801,907
2005	711,700	27.5	2,342	833,478
2006	474,700	13	1,107	262,791
2007	681,800	31.8	2,708	923,279
2008	722,200	26	2,214	799,612
2009	690,000	40.2	3,424	1,181,201
2010	680,670	35.8	3,049	1,037,691
2011	656,800	22.4	1,908	626,513
2012	564,400	40.9	3,483	983,012

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable. Source: NASS

Table 21. Estimated Per Acre and Total Wheat Straw Production, All Wheat, Using the Harvest Index Formula, Based on NASS Acreages and Yields, South East Crop Reporting District, North Dakota, 1980-2012

Year	Acres Harvested	Yield Per Acre	Straw Production per Acre	Total Straw Production[1]
	----acres----	----bushels----	----pounds----	----tons----
1980	1,091,000	18.8	1,601	873,436
1981	1,265,500	26.1	2,223	1,406,537
1982	1,066,500	26.4	2,248	1,198,984
1983	774,500	25.1	2,138	827,835
1984	932,900	36.9	3,143	1,465,919
1985	1,023,000	36.6	3,117	1,594,430
1986	1,015,000	25.8	2,197	1,115,153
1987	997,400	31	2,640	1,316,678
1988	681,500	11.8	1,005	342,449
1989	1,149,900	26.8	2,283	1,312,331
1990	1,220,500	35.6	3,032	1,850,275
1991	972,000	30.9	2,632	1,279,008
1992	1,173,500	45.9	3,909	2,293,741
1993	1,111,900	29.5	2,513	1,396,807
1994	1,107,000	31.5	2,683	1,484,933
1995	1,011,600	29.5	2,513	1,270,807
1996	1,219,400	37.9	3,228	1,968,040
1997	1,115,000	26.5	2,257	1,258,257
1998	840,500	32.7	2,785	1,170,399
1999	775,500	31.1	2,649	1,027,048
2000	744,500	40.8	3,475	1,293,521
2001	731,500	43.8	3,730	1,364,385
2002	617,600	29	2,470	762,700
2003	590,500	48.3	4,114	1,214,551
2004	571,900	49.5	4,216	1,205,519
2005	628,600	34.4	2,930	920,834
2006	n/a	n/a	n/a	n/a
2007	453,100	35.5	3,024	684,909
2008	n/a	n/a	n/a	n/a
2009	413,000	47.8	4,071	840,672
2010	395,800	48.5	4,131	817,459
2011	369,300	30.8	2,623	484,372
2012	267,300	47.3	4,029	538,405

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable. Source: NASS

Table 22. Estimated Per Acre and Total Wheat Straw Production, All Wheat, Using the Harvest Index Formula, Based on NASS Acreages and Yields, South West Crop Reporting District, North Dakota, 1980-2012

Year	Acres Harvested	Yield Per Acre	Straw Production per Acre	Total Straw Production[1]
	----acres----	----bushels----	----pounds----	----tons----
1980	591,500	10.7	911	269,518
1981	979,500	18.6	1,584	775,829
1982	879,000	23.9	2,036	894,613
1983	586,000	24.3	2,070	606,391
1984	760,100	29.3	2,495	948,390
1985	747,000	25.4	2,163	807,984
1986	796,000	27.4	2,334	928,779
1987	786,000	27.3	2,325	913,764
1988	502,000	8.2	698	175,294
1989	845,500	20.4	1,737	734,501
1990	835,500	20.8	1,772	740,045
1991	706,000	25.2	2,146	757,624
1992	904,000	34.7	2,955	1,335,816
1993	879,700	33.3	2,836	1,247,462
1994	873,000	31.7	2,700	1,178,480
1995	905,000	26.6	2,266	1,025,130
1996	1,146,000	29	2,470	1,415,244
1997	990,300	26	2,214	1,096,450
1998	935,800	30.8	2,623	1,227,389
1999	884,100	24.8	2,112	933,688
2000	949,200	35.3	3,006	1,426,859
2001	956,500	37.3	3,177	1,519,296
2002	813,900	17.2	1,465	596,140
2003	1,053,700	27.5	2,342	1,233,952
2004	1,069,100	26.8	2,283	1,220,118
2005	1,138,500	33	2,811	1,599,910
2006	1,118,300	20.8	1,772	990,536
2007	1,123,000	31.9	2,717	1,525,524
2008	990,000	16	1,363	674,534
2009	964,500	44.4	3,782	1,823,618
2010	1,143,300	37.2	3,168	1,811,139
2011	993,400	23.1	1,967	977,203
2012	1,149,400	37.7	3,211	1,845,275

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable. Source: NASS

Year-to-year variability in the acres of wheat harvested and yield per acre resulted in corresponding variability in total straw production. All of the Crop Reporting Districts had total straw production exceeding 800,000 tons per year in 2012 except the Southeast Crop Reporting District which produced just over 500,000 tons. The Northeast District produced 2.9 million tons of total wheat straw and the Northwest District had 3.2 million tons in 2012. Four Crop Reporting Districts (Central, East Central, Northeast, and Southeast) had the lowest wheat acres harvested in 2012 for the 1980-2012 period. Wheat straw production by Crop Reporting District for 2012 is illustrated in Figure 25.

The Northeast and Northwest Districts have historically produced the most wheat straw throughout the 1980-2012 period. The North Central, Southwest, and West Central Districts have seen an in increase in straw production from 1980-2012. Wheat straw production has remained relatively stable in the Central and South Central Districts with some year-to-year variation during the 1980-2012 period with 2012 production at nearly 1 million tons. Wheat straw production in the East Central and Southeast Crop Reporting Districts has been declining during the 1980-2012 period. In recent years the declines have been more pronounced as cropping patterns have shifted to a corn and soybean rotation.

While there is year-to-year wheat variation in acres harvested, yield per acre, and total straw production, in all nine of the Crop Reporting Districts produced substantial quantities of biomass throughout the 1998-2012 reporting period. Estimates of straw production do not take into consideration harvest limitations. A discussion and estimates of recoverable biomass will be examined later in the report.

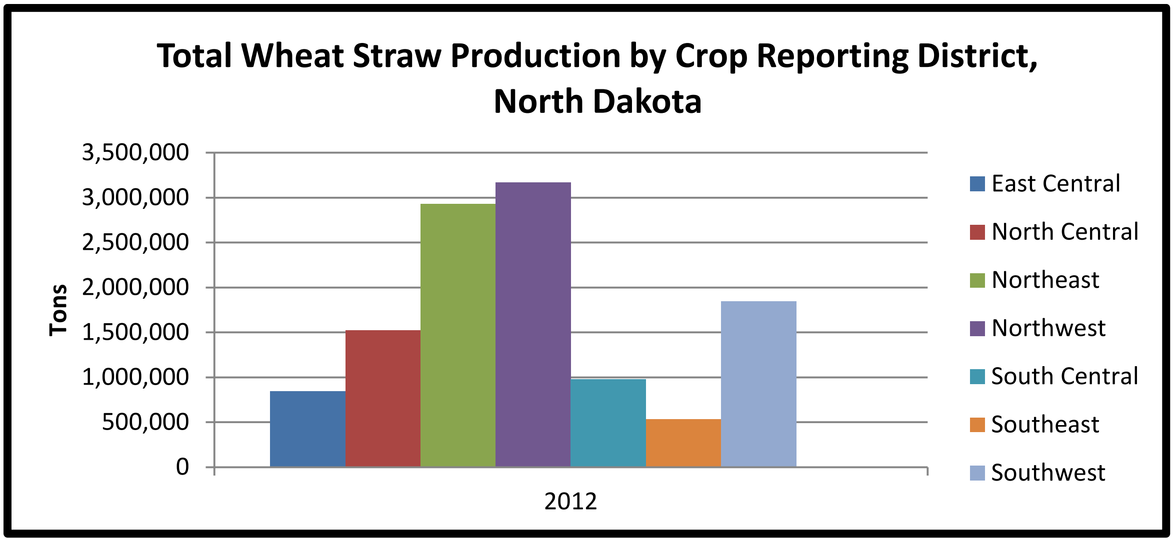


Figure 25. Wheat straw production by NASS Crop Reporting District, 2012

4.5.4.2 Corn Stover

Corn stover is what remains of the corn plant after the corn has been harvested. This includes the corn stalk, leaves, and the corn cob. Corn stover production, like wheat straw, is dependent upon the yield per acre and the total number of acres harvested. In North Dakota, the acres of corn harvested has increased dramatically since 1980. Corn acreage in the state was 290,000 in 1980 and has grown to 3,460,000 in 2012 (Figure 26). Average yields have also increased. Corn yields in 1980 averaged 58.0 bushels per acre while average yields in 2012 were 122 bushels per acre (Figure 27).

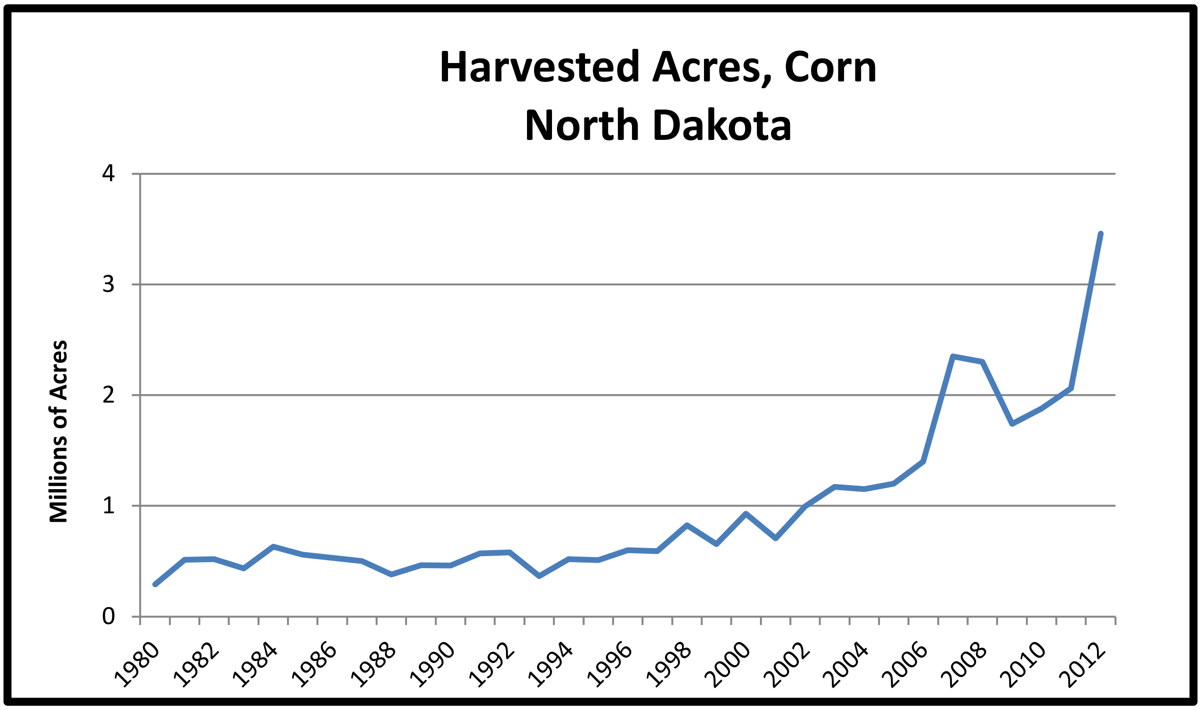


Figure 26. Harvested Acres, Corn, North Dakota

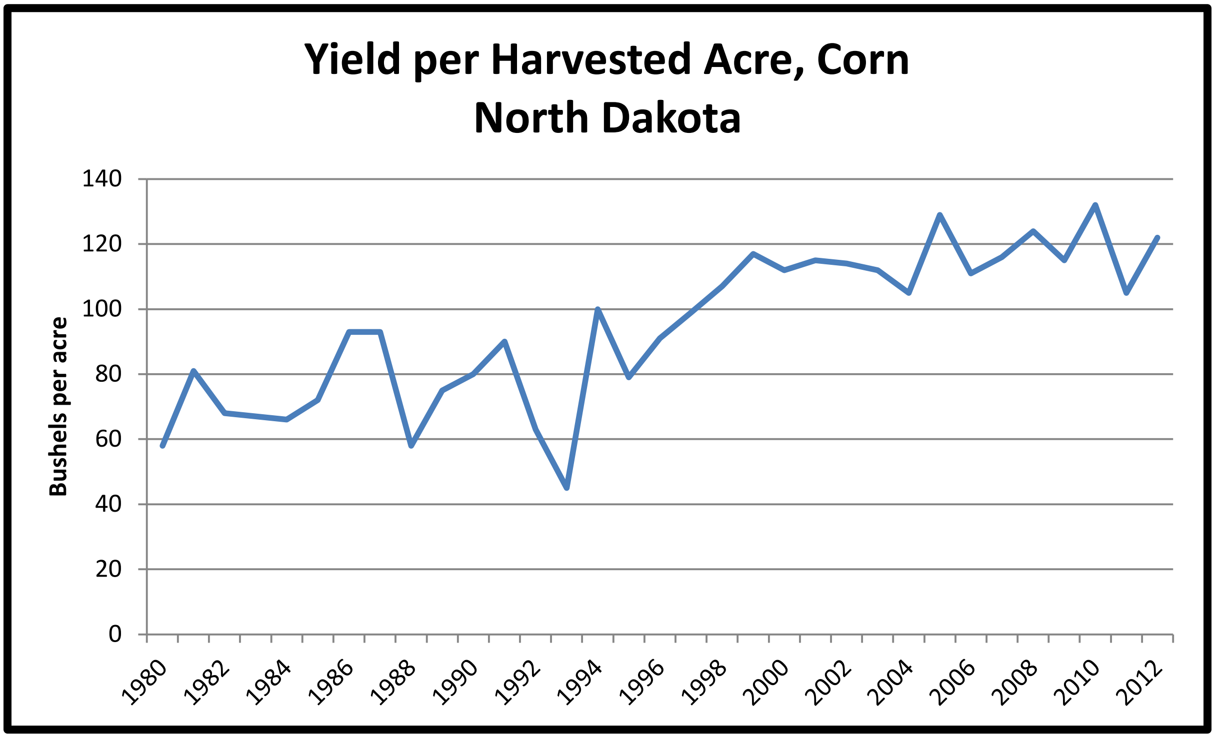


Figure 27. Average Corn Yield per Harvested Acre, North Dakota.

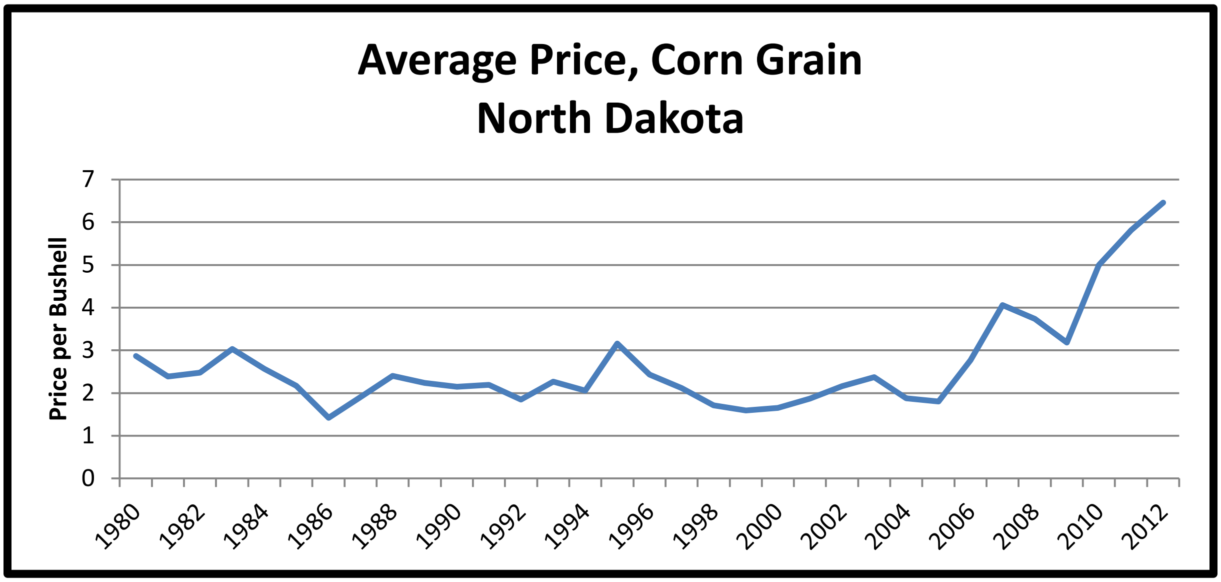


Figure 28. Average Price per Bushel, Corn, North Dakota.

Economic conditions, technological advances and climate variation have all contributed to increased corn acres in North Dakota. Corn prices have risen rapidly in the past several years. (Figure 28). Price has greatly influenced expansion of corn acres. Prior to 2006 corn prices per bushel were only above $2.77 three times from 1980-2005. Beginning in 2006 prices trended upward. In 2011 and 2012 corn prices rose to historic high highs of $5.81 and $6.46 per bushel. Higher prices for corn (and soybeans) and more corn varieties suited for northern climates have resulted in increased corn acreage in North Dakota. Corn production in 2012 was at record level with 3,460,000 acres in corn production; 34.5 percent greater than the previous acreage record (2,350,000) in 2007.

Technological advances and new varieties have also contributed to increased corn acres. Genetically modified seed has resulted in corn varieties with disease and insect resistance, and much less expensive weed control (i.e., Roundup tolerant plants). New corn varieties better suited to shorter growing seasons and a long term wet cycle have also all contributed to changing cropping patterns. Corn can now be grown in every part of the state even in the northern most areas of North Dakota.

Like wheat straw the amount of corn stover produced per acre can be estimated using the Harvest Index formula. The Harvest Index for corn is .50 (Pennington 2013) which is higher than for wheat (.38). The base moisture for corn is 15 percent with the standard measure of 56 pounds per bushel. Like wheat, yield is the determinant variable in corn stover production per acre. The higher the corn yield, the more stover produced per acre. Using the most recent production year average yields (122 bushel per acre in 2012 @ 56 pounds per bushel adjusted to dry weight yields dry grain weigh of 5,807 per acre), per acre corn stover production is estimated as follows:

$$\text{Harvest index} = \frac{\text{dry grain weight}}{\text{total plant dry weight}}$$

$$0.50 = \frac{\text{dry grain weight}}{\text{total plant dry weight}}$$

$$0.50 = \frac{5{,}807}{5{,}807 + x \text{ (where x is the weight of corn stover)}}$$

$$5{,}807 = 2{,}904 + 0.50\,(x)$$

$$2{,}904 = 0.50\,(x)$$

$$x = 5{,}807 \text{ pounds of corn stover per acre}$$

At 122 bushels per acre (2012 average state yield) average corn stover production would be 5,807 pounds of corn stover per acre. North Dakota corn production data for each of the nine Crop Reporting Districts are presented in Tables 23-31. Reporting limitations were the same as for wheat straw discussed earlier. In a few reporting periods production levels by county were not reported due to potential disclosure issues.

Corn acreages have been trending higher since 1980 for all districts with substantial increases in 2012. All Crop Reporting Districts nearly doubled their corn acreage from 2011 to 2012 with the exception of Southeast District, which had a 29.8 percent increase. The Southeast District has historically had the most corn acreage in the state, so crop rotations and substantial acreages already in production may have limited further expansion. The Southeast and East Central districts had over 50 percent of the state's corn production acres. The Southeast Crop Reporting District accounted for 29.7 percent of the state's acreage, and the East Central 24.5 percent in 2012. The Central, Northeast, and South Central accounted for a third of the state corn acres. Combined, the Southeast, East Central, Central, Northeast, and South Central crop reporting district accounted for 86.7 percent of the state' corn acreage.

Corn yields have also increased significantly in all nine of Crop Reporting Districts from 1980 through 2012. In 2012, the corn yield in the Southeast District was 140.0 bushels per acre. The Central, East Central, and Northeast Districts had yields exceeded 125 bushels per acre While there is more biomass available from corn production than wheat on a per acre basis, 3,722 pounds per acres compared to 5,807 pounds per acre for corn stover, in 2012 there was more total biomass produced from wheat that than corn. An estimated 14.4 million tons of biomass was produced as a result of wheat production compared to 10 million tons of biomass from corn production.

Table 23. Per Acre and Total Corn Stover Production for Corn Grain, North Dakota, 1980-2012

Year	Harvested	Yield Per Acre	Corn Stover Per Acre	Total Corn Stover Production[1]
	----acres-----	---bushels---	---Pounds---	----tons----
1980	290,000	58	2,761	400,316
1981	513,000	81	3,856	988,961
1982	520,000	68	3,237	841,568
1983	435,000	67	3,189	693,651
1984	630,000	66	3,142	989,604
1985	560,000	72	3,427	959,616
1986	530,000	93	4,427	1,173,102
1987	500,000	93	4,427	1,106,700
1988	380,000	58	2,761	524,552
1989	465,000	75	3,570	830,025
1990	460,000	80	3,808	875,840
1991	570,000	90	4,284	1,220,940
1992	580,000	63	2,999	869,652
1993	365,000	45	2,142	390,915
1994	520,000	100	4,760	1,237,600
1995	510,000	79	3,760	958,902
1996	600,000	91	4,332	1,299,480
1997	590,000	99	4,712	1,390,158
1998	825,000	107	5,093	2,100,945
1999	655,000	117	5,569	1,823,913
2000	930,000	112	5,331	2,479,008
2001	705,000	115	5,474	1,929,585
2002	995,000	114	5,426	2,699,634
2003	1,170,000	112	5,331	3,118,752
2004	1,150,000	105	4,998	2,873,850
2005	1,200,000	129	6,140	3,684,240
2006	1,400,000	111	5,284	3,698,520
2007	2,350,000	116	5,522	6,487,880
2008	2,300,000	124	5,902	6,787,760
2009	1,740,000	115	5,474	4,762,380
2010	1,880,000	132	6,283	5,906,208
2011	2,060,000	105	4,998	5,147,940
2012	3,460,000	122	5,807	10,046,456

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable.

Table 24. Per Acre and Total Corn Stover Production for Corn Grain, East Central Crop Region, North Dakota, 1980-2012

Year	Harvested	Yield Per Acre	Corn Stover Per Acre	Total Corn Stover Production[1]
	----acres-----	---bushels---	---Pounds---	----tons----
1980	66,000	53.7	2,556	84,352
1981	99,000	81.8	3,894	192,737
1982	108,000	69.2	3,294	177,872
1983	76,500	73.5	3,499	133,822
1984	131,000	64.5	3,070	201,098
1985	120,300	71	3,380	203,283
1986	98,200	102.9	4,898	240,494
1987	95,400	95.9	4,565	216,830
1988	85,000	52.1	2,480	105,398
1989	93,500	50.8	2,418	115,222
1990	88,600	84	3,998	177,129
1991	99,500	95.5	4,546	226,154
1992	120,100	59	2,808	168,644
1993	80,000	46.7	2,223	88,917
1994	102,200	95.5	4,546	232,290
1995	102,700	82	3,903	200,429
1996	127,500	94.3	4,489	286,153
1997	122,900	102.3	4,870	299,230
1998	213,000	111.9	5,326	567,266
1999	143,400	113	5,379	385,660
2000	209,600	115.2	5,484	574,673
2001	124,200	119.7	5,698	353,828
2002	215,000	125.3	5,964	641,160
2003	270,000	127.4	6,064	818,672
2004	295,000	103.2	4,912	724,567
2005	298,000	137.8	6,559	977,333
2006	385,000	116.1	5,526	1,063,824
2007	647,000	122.2	5,817	1,881,709
2008	661,000	135	6,426	2,123,793
2009	477,000	117	5,569	1,328,254
2010	553,000	141.8	6,750	1,866,287
2011	448,000	106.3	5,060	1,234,611
2012	847,000	126.9	6,040	2,558,126

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable.

Table 25. Per Acre and Total Corn Stover Production for Corn Grain, North Central Crop Region, North Dakota, 1980-2012

Year	Harvested	Yield Per Acre	Corn Stover Produced Per Acre	Total Corn Stover Production[1]
	----acres-----	---bushels---	---Pounds---	----tons----
1980	1,400	66.8	3,180	2,226
1981	10,000	70.2	3,342	16,708
1982	12,000	56.1	2,670	16,022
1983	15,600	44.5	2,118	16,522
1984	20,600	44	2,094	21,572
1985	13,000	49.4	2,351	15,284
1986	18,500	72.1	3,432	31,746
1987	17,200	67.6	3,218	27,673
1988	6,300	37.5	1,785	5,623
1989	5,800	44.3	2,109	6,115
1990	9,100	59.1	2,813	12,800
1991	15,800	62.3	2,966	23,427
1992	11,400	32.5	1,547	8,818
1993	1,700	19.3	919	781
1994	7,700	65.7	3,127	12,040
1995	5,200	55.1	2,623	6,819
1996	7,300	63.2	3,008	10,980
1997	10,600	66.6	3,170	16,802
1998	19,200	65.4	3,113	29,885
1999	6,700	85.3	4,060	13,602
2000	23,900	88.7	4,222	50,454
2001	23,200	87.3	4,156	48,204
2002	50,000	78.4	3,732	93,296
2003	54,000	77.6	3,694	99,732
2004	17,000	57.1	2,718	23,103
2005	43,000	93.3	4,441	95,483
2006	59,500	80.3	3,822	113,713
2007	102,700	86.9	4,136	212,406
2008	92,000	92	4,379	201,443
2009	63,500	94	4,474	142,062
2010	67,200	109.8	5,227	175,610
2011	80,400	98.4	4,684	188,290
2012	190,900	98	4,665	445,255

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable.

Table 26. Per Acre and Total Corn Stover Production for Corn Grain, North East Crop Region, North Dakota, 1980-2012

Year	Harvested	Yield Per Acre	Corn Stover Produced Per Acre	Total Corn Stover Production[1]
	----acres-----	---bushels---	---Pounds---	----tons----
1980	9,900	46.1	2,194	10,862
1981	50,200	75.5	3,594	90,204
1982	47,000	56.8	2,704	63,537
1983	34,100	58	2,761	47,072
1984	41,500	58	2,761	57,287
1985	30,400	44.7	2,128	32,341
1986	31,300	94.1	4,479	70,099
1987	31,500	95.6	4,551	71,671
1988	28,600	60	2,856	40,841
1989	23,600	44.2	2,104	24,826
1990	20,500	58.4	2,780	28,493
1991	28,100	92	4,379	61,528
1992	25,500	54.6	2,599	33,137
1993	20,000	49.8	2,371	23,705
1994	28,000	95.7	4,555	63,775
1995	22,200	84.5	4,022	44,244
1996	33,300	86.6	4,122	68,634
1997	35,700	91.5	4,355	77,744
1998	81,800	102	4,855	198,578
1999	45,500	97.2	4,627	105,258
2000	83,100	92.6	4,408	183,142
2001	41,900	107.9	5,136	107,600
2002	98,000	96.9	4,612	226,010
2003	91,000	106.6	5,074	230,874
2004	25,000	62.4	2,970	37,128
2005	93,000	107.7	5,127	238,383
2006	135,000	89.5	4,260	287,564
2007	259,200	114.7	5,460	707,580
2008	265,000	114	5,426	718,998
2009	130,000	113	5,379	349,622
2010	197,500	123.8	5,893	581,922
2011	168,000	99.3	4,727	397,041
2012	339,000	127.9	6,088	1,031,923

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable.

Table 27. Per Acre and Total Corn Stover Production for Corn Grain, North West Crop Region, North Dakota, 1980-2012

Year	Harvested	Yield Per Acre	Corn Stover Produced Per Acre	Total Corn Stover Production[1]
	----acres-----	---bushels---	---Pounds---	----tons----
1980	300	46.7	2,223	333
1981	5,700	56	2,666	7,597
1982	5,500	46.4	2,209	6,074
1983	2,300	47	2,237	2,573
1984	2,700	37.5	1,785	2,410
1985	2,800	46.5	2,213	3,099
1986	4,400	57.7	2,747	6,042
1987	3,500	73.2	3,484	6,098
1988	1,400	19.1	909	636
1989	1,400	29.1	1,385	970
1990	2,200	52.5	2,499	2,749
1991	5,300	56.9	2,708	7,177
1992	2,800	34.1	1,623	2,272
1993	200	34	1,618	162
1994	2,100	64.8	3,085	3,239
1995	1,900	57	2,713	2,578
1996	1,100	73	3,475	1,911
1997	1,600	52.6	2,504	2,003
1998	2,200	62.5	2,975	3,273
1999	1,600	78.9	3,756	3,005
2000	2,500	72	3,427	4,284
2001	4,400	80.5	3,832	8,430
2002	10,000	75	3,570	17,850
2003	14,500	68.3	3,251	23,570
2004	3,500	54.3	2,585	4,523
2005	7,500	86.7	4,127	15,476
2006	10,000	77	3,665	18,326
2007	22,500	79.6	3,789	42,626
2008	15,000	85	4,096	30,345
2009	n/a	n/a	n/a	n/a
2010	11,100	104.2	4,960	27,528
2011	9,300	61.9	2,946	13,701
2012	41,200	89.4	4,255	87,662

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable.

Table 28. Per Acre and Total Corn Stover Production for Corn Grain, South Central Crop Region, North Dakota, 1980-2012

Year	Harvested	Yield Per Acre	Corn Stover Produced Per Acre	Total Corn Stover Production[1]
	----acres-----	---bushels---	---Pounds---	----tons----
1980	2,100	40.3	1,918	2,014
1981	18,800	54.2	2,580	24,251
1982	13,500	43	2,047	13,816
1983	24,500	50	2,380	29,155
1984	23,800	50.5	2,404	28,605
1985	12,800	53.9	2,566	16,420
1986	26,400	70	3,332	43,982
1987	26,200	73.6	3,503	45,894
1988	4,100	51	2,428	4,977
1989	5,400	77.4	3,684	9,947
1990	8,200	82.3	3,918	16,062
1991	22,300	48.9	2,328	25,953
1992	13,700	57.2	2,723	18,651
1993	5,800	40.8	1,942	5,632
1994	18,600	66.1	3,146	29,261
1995	19,600	64.6	3,075	30,135
1996	22,100	62.8	2,989	33,032
1997	19,900	66.4	3,142	31,259
1998	38,900	77.9	3,708	72,121
1999	34,600	89.5	4,260	73,702
2000	43,600	96.3	4,584	99,929
2001	42,700	100.9	4,803	102,541
2002	36,000	72.2	3,437	61,861
2003	49,000	61.8	2,942	72,071
2004	43,000	56.5	2,689	57,822
2005	55,000	105.6	5,027	138,230
2006	31,000	47.4	2,256	34,972
2007	122,700	86.6	4,122	252,895
2008	100,500	88	4,189	210,487
2009	116,000	99	4,712	273,319
2010	122,800	98.7	4,698	288,465
2011	192,000	99.4	4,731	454,281
2012	331,000	87.5	4,165	689,308

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable.

Table 29. Per Acre and Total Corn Stover Production for Corn Grain, Southeast Crop Region, North Dakota, 1980-2012

Year	Harvested	Yield Per Acre	Corn Stover Produced Per Acre	Total Corn Stover Production[1]
	----acres-----	---bushels---	---Pounds---	----tons----
1980	204,500	59.9	2,851	291,539
1981	291,800	84.7	4,032	588,228
1982	290,000	72.4	3,446	499,705
1983	220,100	74.1	3,527	388,164
1984	345,400	73.2	3,484	601,742
1985	339,500	80.1	3,813	647,216
1986	293,300	96.4	4,589	672,924
1987	271,200	98.3	4,679	634,483
1988	227,000	62.2	2,961	336,042
1989	303,400	88.4	4,208	638,329
1990	294,800	82.9	3,946	581,646
1991	341,700	96.8	4,608	787,222
1992	369,700	68.3	3,251	600,962
1993	247,800	44.8	2,133	264,214
1994	328,000	106.2	5,055	829,040
1995	322,100	79.9	3,803	612,512
1996	365,400	94.4	4,493	820,952
1997	355,200	104.8	4,989	885,954
1998	382,200	115.7	5,507	1,052,449
1999	377,600	127.5	6,069	1,145,827
2000	489,300	121.8	5,798	1,418,402
2001	402,200	121.4	5,779	1,162,085
2002	495,000	124.5	5,926	1,466,735
2003	565,000	119.1	5,669	1,601,538
2004	655,000	118.1	5,622	1,841,061
2005	550,000	138.6	6,597	1,814,274
2006	570,000	130.1	6,130	1,764,937
2007	802,000	126.3	6,012	2,410,764
2008	826,000	136	6,474	2,673,597
2009	681,000	125	5,950	2,025,975
2010	649,000	141	6,712	2,177,914
2011	793,000	107.5	5,117	2,028,891
2012	1,029,000	140	6,664	3,428,628

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable.

Table 30. Per Acre and Total Corn Stover Production for Corn Grain, Southwest Crop Region, North Dakota, 1980-2012

Year	Harvested	Yield Per Acre	Corn Stover Produced Per Acre	Total Corn Stover Production[1]
	----acres-----	---bushels---	---Pounds---	----tons----
1980	700	73.4	3,494	1,223
1981	100	39	1,856	93
1982	3,000	43	2,047	3,070
1983	16,000	42	1,999	15,994
1984	12,500	40.5	1,928	12,049
1985	7,800	42.5	2,023	7,890
1986	8,500	60.1	2,861	12,158
1987	8,200	71.1	3,384	13,876
1988	2,500	20.4	971	1,214
1989	2,300	18.9	900	1,035
1990	1,400	27.3	1,300	910
1991	1,400	27.6	1,314	920
1992	1,700	34.1	1,623	1,380
1993	n/a	n/a	n/a	n/a
1994	900	46.9	2,232	1,005
1995	4,100	43.1	2,052	4,206
1996	3,500	52	2,475	4,332
1997	12,500	63.1	3,004	18,772
1998	21,500	61.9	2,946	31,674
1999	11,800	60.9	2,899	17,103
2000	22,000	50.1	2,385	26,232
2001	20,300	69.3	3,299	33,482
2002	13,000	50.8	2,418	15,718
2003	14,000	40	1,904	13,328
2004	15,500	36.8	1,752	13,576
2005	20,000	68	3,237	32,368
2006	26,500	41.5	1,975	26,174
2007	45,500	60.7	2,889	65,732
2008	27,300	45	2,142	29,238
2009	n/a	n/a	n/a	n/a
2010	33,900	83.3	3,965	67,208
2011	45,000	79	3,760	84,609
2012	100,400	62.5	2,975	149,345

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable.

Table 31. Per Acre and Total Corn Stover Production for Corn Grain, West Central Crop Region, North Dakota, 1980-2012

Year	Harvested	Yield Per Acre	Corn Stover Produced Per Acre	Total Corn Stover Production[1]
	----acres-----	---bushels---	---Pounds---	----tons----
1980	400	60.5	2,880	576
1981	4,800	54.5	2,594	6,226
1982	11,000	56.3	2,680	14,739
1983	15,500	49.5	2,356	18,261
1984	7,800	54	2,570	10,025
1985	5,400	57.5	2,737	7,390
1986	8,500	79.6	3,789	16,103
1987	8,900	77.8	3,703	16,480
1988	4,000	57.7	2,747	5,493
1989	3,700	50.6	2,409	4,456
1990	5,300	58.2	2,770	7,341
1991	8,200	52.7	2,509	10,285
1992	8,500	43.3	2,061	8,760
1993	500	26.4	1,257	314
1994	3,500	87.5	4,165	7,289
1995	7,300	70.5	3,356	12,249
1996	6,000	64.9	3,089	9,268
1997	6,000	54.3	2,585	7,754
1998	17,400	82.4	3,922	34,124
1999	6,100	90.6	4,313	13,153
2000	9,200	92.5	4,403	20,254
2001	6,200	105.5	5,022	15,568
2002	12,000	94.2	4,484	26,904
2003	17,500	66.3	3,156	27,614
2004	11,000	58.2	2,770	15,237
2005	19,500	92.8	4,417	43,069
2006	35,000	74	3,522	61,642
2007	56,200	84.7	4,032	113,291
2008	33,700	82	3,903	65,769
2009	40,500	100	4,760	96,390
2010	43,500	112	5,331	115,954
2011	47,300	103.6	4,931	116,627
2012	127,500	89.8	4,275	272,498

[1] Dry weight basis. Estimates represent total straw production, of which only a portion of which is recoverable.

4.5.5 Recoverable Biomass

Wheat and corn acreages in North Dakota produce a large volume of biomass. However, corn stover and wheat straw production estimates do not take into consideration harvest limitations. Not all biomass produced can be recovered using currently available gathering techniques. Petrolia (2009) estimates corn stover has a 35 percent recoverable harvest rate. Lundstrom (1994) estimates 43 percent of total straw production can be recovered.

Recoverable biomass was estimated by applying the recoverable harvest rate for wheat straw (43 percent) reported by Lundstrum (1994) and the recoverable harvest rate for corn stover (35 percent) reported by Petrolia (2009) to estimates of biomass production using the Harvest Index formula.

Total recoverable biomass from the two crops state wide during the 1980-2012 period ranged from just over 2 million tons in 1988 to 9.7 million tons in 2012 (Table 39). Tables 32-41 detail estimated recoverable biomass for the state and for each crop reporting district.

There is sufficient recoverable biomass produced in North Dakota to support many AFEX pelleting depots. If the recoverable biomass produced in the state from 2006 to 2012 were olympic averaged (high and low values dropped), 193 110-tons per day depots could be supplied with available biomass. While it is unlikely that that the theoretical maximum number of depots would be achieved due to any number of factors, (e.g., constraints to producer participation, logistical constraints) the estimate of the maximum number of depots illustrates a sufficient supply of biomass is available to support a system of biomass pretreatment depots in North Dakota.

Table 32. Wheat Straw and Corn Stover Biomass Production and Recoverable, and Total Recoverable Biomass, North Dakota, 1980 - 2012

	Wheat Straw		Corn Stover		Total Recoverable
Year	Production	Recoverable	Production	Recoverable	Biomass
	--tons--				
1980	7,660,644	3,294,077	400,316	140,111	3,434,188
1981	14,137,788	6,079,249	989,961	346,487	6,425,735
1982	14,071,314	6,050,665	841,568	294,549	6,345,214
1983	8,253,438	3,548,978	693,651	242,778	3,791,756
1984	12,095,960	5,201,263	989,604	346,361	5,547,624
1985	13,749,079	5,912,104	959,616	335,866	6,247,970
1986	12,462,525	5,358,886	1,173,102	410,586	5,769,471
1987	11,682,978	5,023,681	1,106,700	387,345	5,411,026
1988	4,402,739	1,893,178	524,552	183,593	2,076,771
1989	10,337,530	4,445,138	830,025	290,509	4,735,647
1990	16,400,159	7,052,068	875,840	306,544	7,358,612
1991	12,923,882	5,557,269	1,220,940	427,329	5,984,598
1992	19,987,410	8,594,586	869,652	304,378	8,898,965
1993	14,257,194	6,130,593	390,915	136,820	6,267,414
1994	15,170,395	6,523,270	1,237,600	433,160	6,956,430
1995	12,778,585	5,494,791	958,902	335,616	5,830,407
1996	16,840,948	7,241,608	1,299,480	454,818	7,696,426
1997	11,408,629	4,905,711	1,390,158	486,555	5,392,266
1998	13,218,267	5,683,855	2,100,945	735,331	6,419,185
1999	10,322,242	4,438,564	1,823,913	638,370	5,076,934
2000	13,348,144	5,739,702	2,479,008	867,653	6,607,355
2001	12,450,601	5,353,759	1,929,585	675,355	6,029,113
2002	9,201,575	3,956,677	2,699,634	944,872	4,901,549
2003	13,501,324	5,805,569	3,118,752	1,091,563	6,897,133
2004	13,045,034	5,609,365	2,873,850	1,005,848	6,615,212
2005	12,942,364	5,565,216	3,684,240	1,289,484	6,854,700
2006	10,731,902	4,614,718	3,698,520	1,294,482	5,909,200
2007	12,777,754	5,494,434	6,487,880	2,270,758	7,765,192
2008	13,245,393	5,695,519	6,787,760	2,375,716	8,071,235
2009	13,483,922	5,798,087	4,762,380	1,666,833	7,464,920
2010	15,381,417	6,614,009	5,906,208	2,067,173	8,681,182
2011	8,503,087	3,656,328	5,147,940	1,801,779	5,458,107
2012	14,440,817	6,209,551	10,046,456	3,516,260	9,725,811

Table 33. Wheat Straw and Corn Stover Biomass Production and Recoverable Biomass, Central Crop Reporting District, 1980 - 2012

	Wheat Straw		Corn Stover		Total Recoverable Biomass
Year	Production	Recoverable	Production	Recoverable	
	---tons---				
1980	803,021	345,299	7,405	2,592	347,891
1981	1,588,131	682,897	62,924	22,023	704,920
1982	1,413,525	607,816	41,555	14,544	622,360
1983	819,169	352,243	43,718	15,301	367,544
1984	1,257,086	540,547	54,789	19,176	559,723
1985	1,341,083	576,666	20,049	7,017	583,683
1986	1,299,551	558,807	79,918	27,971	586,778
1987	1,196,595	514,536	72,522	25,383	539,919
1988	354,843	152,583	24,406	8,542	161,125
1989	818,562	351,982	31,622	11,068	363,050
1990	1,960,594	843,056	48,746	17,061	860,117
1991	1,370,707	589,404	78,106	27,337	616,741
1992	1,899,009	816,574	26,779	9,373	825,947
1993	1,488,293	639,966	7,111	2,489	642,455
1994	1,583,045	680,709	59,495	20,823	701,533
1995	1,210,246	520,406	45,098	15,784	536,190
1996	1,688,152	725,905	64,597	22,609	748,514
1997	1,022,921	439,856	50,509	17,678	457,534
1998	1,008,063	433,467	111,731	39,106	472,573
1999	884,898	380,506	66,519	23,282	403,788
2000	1,014,254	436,129	101,694	35,593	471,722
2001	1,002,130	430,916	97,716	34,201	465,117
2002	686,277	295,099	133,832	46,841	341,941
2003	1,196,173	514,355	230,848	80,797	595,151
2004	1,136,491	488,691	156,985	54,945	543,636
2005	1,133,287	487,314	329,654	115,379	602,692
2006	889,690	382,567	326,879	114,408	496,974
2007	1,081,993	465,257	801,142	280,400	745,657
2008	1,304,993	561,147	731,731	256,106	817,253
2009	1,305,721	561,460	461,244	161,435	722,896
2010	1,265,066	543,978	604,796	211,679	755,657
2011	752,821	323,713	630,619	220,717	544,430
2012	928,910	399,431	1,385,227	484,829	884,261

Table 34. Wheat Straw and Corn Stover Biomass Production and Recoverable Biomass, East Central Crop Reporting District, 1980 - 2012

Year	Wheat Straw		Corn Stover		Total Recoverable Biomass
	Production	Recoverable	Production	Recoverable	
	--tons--				
1980	1,143,546	491,725	84,352	29,523	521,248
1981	1,784,794	767,461	192,737	67,458	834,919
1982	1,851,085	795,966	177,872	62,255	858,221
1983	1,016,400	437,052	133,822	46,838	483,890
1984	1,794,373	771,580	201,098	70,384	841,965
1985	1,881,362	808,986	203,283	71,149	880,135
1986	1,381,066	593,858	240,494	84,173	678,031
1987	1,554,111	668,268	216,830	75,891	744,158
1988	808,638	347,714	105,398	36,889	384,604
1989	1,508,810	648,788	115,222	40,328	689,116
1990	2,709,787	1,165,208	177,129	61,995	1,227,203
1991	1,760,323	756,939	226,154	79,154	836,093
1992	2,719,119	1,169,221	168,644	59,026	1,228,247
1993	1,551,949	667,338	88,917	31,121	698,459
1994	1,619,228	696,268	232,290	81,302	777,570
1995	1,478,088	635,578	200,429	70,150	705,728
1996	2,242,994	964,487	286,153	100,154	1,064,641
1997	1,414,670	608,308	299,230	104,730	713,038
1998	1,633,817	702,541	567,266	198,543	901,084
1999	1,437,547	618,145	385,660	134,981	753,126
2000	1,712,327	736,301	574,673	201,136	937,436
2001	1,647,973	708,629	353,828	123,840	832,468
2002	1,213,711	521,896	641,160	224,406	746,302
2003	1,679,842	722,332	818,672	286,535	1,008,867
2004	1,480,895	636,785	724,567	253,599	890,383
2005	1,286,624	553,248	977,333	342,066	895,315
2006	0	0	1,063,824	372,339	372,339
2007	994,682	427,713	1,881,709	658,598	1,086,311
2008	0	0	2,123,793	743,328	743,328
2009	1,042,419	448,240	1,328,254	464,889	913,129
2010	1,163,677	500,381	1,866,287	653,200	1,153,581
2011	583,244	250,795	1,234,611	432,114	682,909
2012	844,741	363,239	2,558,126	895,344	1,258,583

Table 35. Wheat Straw and Corn Stover Biomass Production and Recoverable Biomass, North Central Crop Reporting District, 1980 - 2012

	Wheat Straw		Corn Stover		Total Recoverable Biomass
Year	Production	Recoverable	Production	Recoverable	
	---tons---				
1980	867,892	373,194	2,226	779	373,973
1981	1,529,476	657,675	16,708	5,848	663,522
1982	1,499,262	644,683	16,022	5,608	650,291
1983	859,136	369,429	16,522	5,783	375,211
1984	1,094,240	470,523	21,572	7,550	478,073
1985	1,463,747	629,411	15,284	5,350	634,761
1986	1,327,695	570,909	31,746	11,111	582,020
1987	954,461	410,418	27,673	9,685	420,104
1988	427,139	183,670	5,623	1,968	185,638
1989	1,005,560	432,391	6,115	2,140	434,531
1990	1,858,613	799,204	12,800	4,480	803,684
1991	1,378,104	592,585	23,427	8,200	600,784
1992	1,857,736	798,827	8,818	3,086	801,913
1993	1,677,556	721,349	781	273	721,622
1994	1,790,259	769,811	12,040	4,214	774,025
1995	1,322,686	568,755	6,819	2,387	571,142
1996	1,540,615	662,465	10,980	3,843	666,308
1997	1,073,080	461,424	16,802	5,881	467,305
1998	1,089,178	468,347	29,885	10,460	478,806
1999	522,938	224,863	13,602	4,761	229,624
2000	1,086,536	467,211	50,454	17,659	484,870
2001	891,481	383,337	48,204	16,871	400,208
2002	778,354	334,692	93,296	32,654	367,346
2003	1,263,601	543,349	99,732	34,906	578,255
2004	1,129,457	485,666	23,103	8,086	493,752
2005	1,082,288	465,384	95,483	33,419	498,803
2006	1,184,557	509,359	113,713	39,800	549,159
2007	1,379,516	593,192	212,406	74,342	667,534
2008	1,380,325	593,540	201,443	70,505	664,045
2009	1,624,662	698,605	142,062	49,722	748,327
2010	1,645,135	707,408	175,610	61,463	768,872
2011	965,482	415,157	188,290	65,902	481,059
2012	1,521,753	654,354	445,255	155,839	810,193

Table 36. Wheat Straw and Corn Stover Biomass Production and Recoverable Biomass, North East Crop Reporting District, 1980 - 2012

	Wheat Straw		Corn Stover		Total Recoverable Biomass
Year	Production	Recoverable	Production	Recoverable	
	---tons---				
1980	1,786,582	768,230	10,862	3,802	772,032
1981	3,103,028	1,334,302	90,204	31,572	1,365,874
1982	3,245,888	1,395,732	63,537	22,238	1,417,970
1983	1,780,735	765,716	47,072	16,475	782,191
1984	2,863,090	1,231,129	57,287	20,050	1,251,179
1985	3,394,175	1,459,495	32,341	11,320	1,470,815
1986	2,604,995	1,120,148	70,099	24,535	1,144,683
1987	2,879,940	1,238,374	71,671	25,085	1,263,459
1988	1,391,582	598,380	40,841	14,294	612,675
1989	2,815,065	1,210,478	24,826	8,689	1,219,167
1990	3,692,396	1,587,730	28,493	9,973	1,597,703
1991	3,003,675	1,291,580	61,528	21,535	1,313,115
1992	4,770,890	2,051,483	33,137	11,598	2,063,081
1993	2,027,208	871,699	23,705	8,297	879,996
1994	2,632,372	1,131,920	63,775	22,321	1,154,241
1995	2,368,565	1,018,483	44,244	15,486	1,033,968
1996	2,933,387	1,261,356	68,634	24,022	1,285,378
1997	2,051,600	882,188	77,744	27,210	909,398
1998	2,336,527	1,004,707	198,578	69,502	1,074,209
1999	2,158,287	928,063	105,258	36,840	964,904
2000	2,714,393	1,167,189	183,142	64,100	1,231,289
2001	2,059,315	885,505	107,600	37,660	923,165
2002	2,182,273	938,377	226,010	79,103	1,017,481
2003	2,955,153	1,270,716	230,874	80,806	1,351,522
2004	2,846,784	1,224,117	37,128	12,995	1,237,112
2005	2,138,287	919,464	238,383	83,434	1,002,898
2006	2,498,944	1,074,546	287,564	100,647	1,175,193
2007	2,644,701	1,137,221	707,580	247,653	1,384,874
2008	3,459,235	1,487,471	718,998	251,649	1,739,120
2009	2,829,721	1,216,780	349,622	122,368	1,339,148
2010	3,153,854	1,356,157	581,922	203,673	1,559,830
2011	2,301,364	989,587	397,041	138,964	1,128,551
2012	2,929,590	1,259,724	1,031,923	361,173	1,620,897

Table 37. Wheat Straw and Corn Stover Biomass Production and Recoverable Biomass, North West Crop Reporting District, 1980 - 2012

Year	Wheat Straw		Corn Stover		Total Recoverable Biomass
	Production	Recoverable	Production	Recoverable	
	---tons---				
1980	1,309,009	562,874	333	117	562,991
1981	2,124,948	913,728	7,597	2,659	916,387
1982	2,070,589	890,353	6,074	2,126	892,479
1983	1,339,256	575,880	2,573	901	576,781
1984	1,303,911	560,682	2,410	843	561,525
1985	1,624,311	698,454	3,099	1,085	699,538
1986	2,166,003	931,381	6,042	2,115	933,496
1987	1,351,329	581,072	6,098	2,134	583,206
1988	658,293	283,066	636	223	283,289
1989	1,247,587	536,462	970	339	536,802
1990	2,234,583	960,871	2,749	962	961,833
1991	2,009,710	864,175	7,177	2,512	866,688
1992	2,935,104	1,262,095	2,272	795	1,262,890
1993	2,815,734	1,210,766	162	57	1,210,822
1994	2,747,342	1,181,357	3,239	1,134	1,182,490
1995	2,338,993	1,005,767	2,578	902	1,006,669
1996	2,741,081	1,178,665	1,911	669	1,179,334
1997	1,889,646	812,548	2,003	701	813,249
1998	2,594,668	1,115,707	3,273	1,145	1,116,853
1999	1,881,317	808,966	3,005	1,052	810,018
2000	2,376,777	1,022,014	4,284	1,499	1,023,513
2001	1,978,101	850,584	8,430	2,951	853,534
2002	1,862,446	800,852	17,850	6,248	807,099
2003	2,128,648	915,319	23,570	8,250	923,568
2004	2,079,949	894,378	4,523	1,583	895,961
2005	2,595,657	1,116,132	15,476	5,417	1,121,549
2006	2,026,161	871,249	18,326	6,414	877,663
2007	2,466,954	1,060,790	42,626	14,919	1,075,709
2008	2,624,380	1,128,483	30,345	10,621	1,139,104
2009	3,200,629	1,376,271	0	0	1,376,271
2010	2,903,625	1,248,559	27,528	9,635	1,258,194
2011	911,558	391,970	13,701	4,795	396,765
2012	3,168,985	1,362,664	87,662	30,682	1,393,345

Table 38. Wheat Straw and Corn Stover Biomass Production and Recoverable Biomass, South Central Crop Reporting District, 1980 - 2012

	Wheat Straw		Corn Stover		Total Recoverable Biomass
Year	Production	Recoverable	Production	Recoverable	
	---tons---				
1980	184,447	79,312	2,014	705	80,017
1981	737,772	317,242	24,251	8,488	325,730
1982	687,820	295,763	13,816	4,836	300,598
1983	419,265	180,284	29,155	10,204	190,488
1984	665,144	286,012	28,605	10,012	296,024
1985	721,087	310,067	16,420	5,747	315,814
1986	641,616	275,895	43,982	15,394	291,289
1987	609,787	262,208	45,894	16,063	278,271
1988	66,802	28,725	4,977	1,742	30,467
1989	258,316	111,076	9,947	3,482	114,557
1990	396,817	170,631	16,062	5,622	176,253
1991	576,713	247,987	25,953	9,084	257,070
1992	1,016,196	436,964	19,651	6,878	443,842
1993	871,595	374,786	5,632	1,971	376,757
1994	867,512	373,030	29,261	10,241	383,272
1995	713,171	306,663	30,135	10,547	317,210
1996	982,879	422,638	33,032	11,561	434,199
1997	678,774	291,873	31,259	10,941	302,813
1998	826,802	355,525	72,121	25,243	380,768
1999	547,904	235,599	73,702	25,796	261,394
2000	889,545	382,505	99,929	34,975	417,480
2001	835,928	359,449	102,541	35,889	395,338
2002	224,053	96,343	61,861	21,651	117,994
2003	684,982	294,542	72,071	25,225	319,767
2004	801,907	344,820	57,822	20,238	365,058
2005	833,478	358,395	138,230	48,381	406,776
2006	262,791	113,000	34,972	12,240	125,240
2007	923,279	397,010	252,895	88,513	485,523
2008	799,612	343,833	210,487	73,671	417,504
2009	1,181,201	507,916	273,319	95,662	603,578
2010	1,037,691	446,207	288,465	100,963	547,170
2011	626,513	269,400	454,218	158,976	428,377
2012	983,012	422,695	689,308	241,258	663,953

Table 39. Wheat Straw and Corn Stover Biomass Production and Recoverable Biomass, South Eastl Crop Reporting District, 1980 - 2012

	Wheat Straw		Corn Stover		Total Recoverable Biomass
Year	Production	Recoverable	Production	Recoverable	
	---tons---				
1980	873,436	375,578	291,539	102,039	477,616
1981	1,406,537	604,811	588,228	205,880	810,691
1982	1,198,984	515,563	499,705	174,897	690,460
1983	827,835	355,969	388,164	135,857	491,826
1984	1,465,919	630,345	601,742	210,610	840,955
1985	1,594,430	685,605	647,216	226,526	912,130
1986	1,115,153	479,516	672,924	235,523	715,039
1987	1,316,678	566,172	634,483	222,069	788,241
1988	342,449	147,253	336,048	117,617	264,870
1989	1,312,331	564,302	638,329	223,415	787,718
1990	1,850,275	795,618	581,646	203,576	999,195
1991	1,279,008	549,974	787,222	275,528	825,501
1992	2,293,741	986,309	600,962	210,337	1,196,645
1993	1,396,807	600,627	264,214	92,475	693,102
1994	1,484,933	638,521	829,040	290,164	928,685
1995	1,207,807	519,357	612,512	214,379	733,736
1996	1,968,040	846,257	820,952	287,333	1,133,590
1997	1,258,257	541,051	885,954	310,084	851,134
1998	1,170,399	503,272	1,052,449	368,357	871,629
1999	1,027,048	441,631	1,145,827	401,040	842,670
2000	1,293,521	556,214	1,418,402	496,441	1,052,655
2001	1,364,385	586,686	1,162,085	406,730	993,415
2002	762,700	327,961	1,466,735	513,357	841,318
2003	1,214,551	522,257	1,601,538	560,538	1,082,795
2004	1,205,519	518,373	1,841,061	644,371	1,162,744
2005	920,834	395,959	1,814,274	634,996	1,030,955
2006	0	0	1,764,937	617,728	617,728
2007	684,909	294,511	2,410,764	843,767	1,138,278
2008	0	0	2,673,597	935,759	935,759
2009	840,672	361,489	2,025,975	709,091	1,070,580
2010	817,459	351,508	2,177,914	762,270	1,113,778
2011	484,372	208,280	2,028,891	710,112	918,391
2012	538,405	231,514	3,428,628	1,200,020	1,431,534

Table 40. Wheat Straw and Corn Stover Biomass Production and Recoverable Biomass, South West Crop Reporting District, 1980 - 2012

	Wheat Straw		Corn Stover		Total Recoverable Biomass
Year	Production	Recoverable	Production	Recoverable	
	---tons---				
1980	269,518	115,893	1,223	428	116,321
1981	775,829	333,607	93	33	333,639
1982	894,613	384,684	3,070	1,075	385,758
1983	606,391	260,748	15,994	5,598	266,346
1984	948,390	407,808	12,049	4,217	412,025
1985	807,984	347,433	7,890	2,761	350,195
1986	928,779	399,375	12,158	4,255	403,630
1987	913,764	392,918	13,876	4,857	397,775
1988	175,294	75,376	1,214	425	75,801
1989	734,501	315,835	1,035	362	316,198
1990	740,045	318,220	910	318	318,538
1991	757,624	325,778	920	322	326,100
1992	1,335,816	574,401	1,380	483	574,884
1993	1,247,462	536,409	0	0	536,409
1994	1,178,480	506,746	1,005	352	507,098
1995	1,025,130	440,806	4,206	1,472	442,278
1996	1,415,244	608,555	4,332	1,516	610,071
1997	1,096,450	471,473	18,772	6,570	478,044
1998	1,227,389	527,777	31,674	11,086	538,863
1999	933,688	401,486	17,103	5,986	407,472
2000	1,426,859	613,549	26,232	9,181	622,731
2001	1,519,296	653,297	33,482	11,719	665,016
2002	596,140	256,340	15,718	5,501	261,841
2003	1,233,952	530,599	13,328	4,665	535,264
2004	1,220,118	524,651	13,576	4,751	529,402
2005	1,599,910	687,961	32,368	11,329	699,290
2006	990,536	425,931	26,174	9,161	435,091
2007	1,525,524	655,975	65,732	23,006	678,982
2008	674,534	290,050	29,238	10,233	300,283
2009	1,823,618	784,156	0	0	784,156
2010	1,811,139	778,790	67,208	23,523	802,313
2011	977,203	420,197	84,609	29,613	449,810
2012	1,845,275	793,468	149,345	52,271	845,739

Table 41. Wheat Straw and Corn Stover Biomass Production and Recoverable Biomass, West Central Crop Reporting District, 1980 - 2012

Year	Wheat Straw		Corn Stover		Total Recoverable Biomass
	Production	Recoverable	Production	Recoverable	
	--------------------tons--------------------				
1980	406,796	174,922	576	202	175,124
1981	931,921	400,726	6,226	2,179	402,905
1982	968,957	416,652	14,739	5,159	421,810
1983	600,595	258,256	18,261	6,391	264,647
1984	707,067	304,039	10,025	3,509	307,548
1985	934,370	401,779	7,390	2,587	404,366
1986	979,641	421,246	16,103	5,636	426,882
1987	689,374	296,431	16,480	5,768	302,199
1988	179,441	77,160	5,493	1,923	79,082
1989	616,735	265,196	4,456	1,560	266,756
1990	963,872	414,465	7,341	2,570	417,035
1991	796,949	342,688	10,285	3,600	346,288
1992	1,321,878	568,408	8,760	3,066	571,473
1993	1,257,711	540,816	314	110	540,926
1994	1,267,776	545,144	7,289	2,551	547,695
1995	1,050,552	451,737	12,249	4,287	456,024
1996	1,307,231	562,110	9,268	3,244	565,353
1997	979,359	421,124	7,754	2,714	423,838
1998	1,222,082	525,495	34,124	11,943	537,439
1999	923,950	397,298	13,153	4,604	401,902
2000	988,550	425,077	20,254	7,089	432,165
2001	1,182,985	508,683	15,568	5,449	514,132
2002	903,164	388,361	26,904	9,416	397,777
2003	1,145,370	492,509	27,614	9,665	502,174
2004	1,155,629	496,921	15,237	5,333	502,253
2005	1,341,777	576,964	43,069	15,074	592,038
2006	981,804	422,176	61,642	21,575	443,750
2007	1,073,231	461,489	113,291	39,652	501,141
2008	609,380	262,033	65,769	23,019	285,053
2009	1,764,213	758,612	96,390	33,737	792,348
2010	1,602,325	689,000	115,954	40,584	729,583
2011	286,703	123,282	116,627	40,819	164,101
2012	1,564,845	672,883	272,498	95,374	768,258

4.5.6 Feedstock Cost

The cost for wheat straw has previously been estimated to be \$37 to \$44 per ton (Coon and Leistritz, 2006; Coon and Leistritz, 2010). To account for market changes estimates were updated to reflect current conditions. Biomass cost estimates for wheat straw were based on the nutrient value of the straw, cost for baling and transportation and a producer incentive. Biomass cost for corn stover costs were calculated similarly with inclusion of an addition cost for cutting the corn stalks and raking the corn residue into windrows for baling. Both estimates include a \$5 per ton producer incentive payment.

4.5.6.1 Nutrient Value of Wheat Straw

Wheat straw has a soil nutrient value. Removing the straw would require replacing the nitrogen, phosphates, and potash in the straw with commercial fertilizers. Jones (2003) states that 2-ton per acre wheat yields would have the following nutrient value:

4000 pound/acre = 30 pounds of nitrogen (N)
4000 pound/acre = 9 pounds phosphate ((P_20_5)
4000 pound/acre = 65 pounds of potash(K_20)

Converting to a percentage of weight basis:

N = 0.75 percent of straw weight
(P_20_5) = 0.225 percent of straw weight
(K_20) = 1.625 percent of straw weigh

Using 2012 wheat yields (43.7 bushels per acres produces 3,722 pounds of wheat straw) to estimate the nutrient values would result in the following

N = 3,722 pounds of straw x .0075 = 27.9 pounds of N
(P_20_5) = 3,722 pounds of straw x .00225 = 8.4 pounds of (P_20_5)
(K_20) = 3,722 pounds of straw x .01625 = 60.5 pounds of (K_20)

Fertilizer prices have been significantly higher in recent years as prices have tracked higher with corn prices to record levels. More recently in 2013, fertilizer prices moderated as corn prices dropped. As projecting fertilizer prices is beyond the scope of this study, fall 2013 prices will be used (Perry 2013).

Fall 2013 fertilizer prices were as follows:

Nitrogen:	NH_3 (82-0-0)	=	\$640/ton (\$0.390/unit N)
	Urea (46-0-0)	=	\$415/ton (0.451/unit N)
Phosphorus:	P_20_5 (11-52-0)	=	\$495/ton (\$0.476/unit P_20_5)
Potash:	K_20 (0-0-60)	=	\$430/ton (\$0.358/unit K_20)

Using the above prices (anhydrous ammonia for N) for fertilizer, the per acre straw value fora 43.7 bushels per acre wheat crop would be calculated as follows:

N	=	27.9 pounds/acre	x	\$0.390	=	\$10.88/acre
P_20_5	=	8.4 pounds/acre	x	\$0.476	=	\$4.00/acre
K_20	=	60.5 pounds/acre	x	\$0.358	=	\$21.66/acre
Wheat Straw Nutrient Value:						\$36.54/acre

Wheat straw nutrient value per acre (\$36.54) is based on all straw produced returned to the soil. The per acre nutrient value can be used to calculate the per ton price. Per acre nutrient value of wheat straw was based on the 2012 state average wheat yield of 43.7 bushels per acre which produced 3,722 pounds of wheat straw per acre or 1.86 tons per acre. Nutrient value of the straw on a per ton basis was calculated by dividing the total nutrient value of the straw per acre (\$36.54/acre) by the tons of straw produced per acre (1.86 ton/acre) for a nutrient value of \$19.65/ton.

Per ton and per acre values are based on all straw produced. As previously discussed actual biomass recovery is less than 100 percent and for wheat straw is estimated to be 43 percent (Lundstrom (1994). Assuming a 43 percent recovery rate would reduce the per acre nutrient value to \$15.71 (\$36.54/acre x .43 recovery).

Current yields and price of commercial fertilizer has increased the nutrient value compared to previous assessments. The nutrient value of wheat straw was estimated to be \$28.94 in 2010 (Coon and Leistritz, 2010). Wheat yields used to estimate nutrient value were higher (43.7 bushels per acre versus 32.5 bushels per acre), and fertilizer prices for N and P_20_5 were up significantly with K_20 slightly lower than the previous analysis.

Because wheat straw would be typically be purchased by weight, yield changes would not affect the cost per ton of biomass. If yields decline, there would be less straw and nutrient value, but cost per ton would be the same. However, if fertilizer prices were to rise, the nutrient value would increase accordingly.

4.5.6.2 Nutrient Value of Corn Stover

Like wheat straw, corn stover has a soil nutrient value. The procedures for calculating nutrient value of corn stover are the same as for wheat straw. Gould (2007) reported the following nutrient value for corn stover:

2000 pound/acre = 13.6 pounds of nitrogen (N)

2000 pound/acre = 3.6 pounds phosphate ((P_20_5)

2000 pound/acre = 19.7pounds of potash(K_20)

Converting to a percentage basis:

N = 0.68 percent of straw weight

(P_20_5) = 0.18 percent of straw weight

(K_20) = .985 percent of straw weigh

The average corn yield in 2012 of 122 bushels per acre would yield 5,807 pounds of stover per acre. Corn stover would have the following nutrient value:

5,807 pounds of stover x .68 = 39.5 pounds of N

5,807 pounds of stover x .18 = 10.5 pounds of (P_20_5)

5,807 pounds of stover x .985 = 57.2 pounds of (K_20)

Corn stover nutrient values were also based on fall 2013 fertilizer prices:

Nitrogen: NH_3 (82-0-0) = \$640/ton (\$0.390/unit N)
Urea (46-0-0) = \$415/ton (0.451/unit N
Phosphorus: P_20_5 (11-52-0) = \$495/ton (\$0.476/unit P_20_5)
Potash: K_20 (0-0-60) = \$430/ton (\$0.358/unit K_20)

Corn stover nutrient values were estimated to be:

N = 39.5 pounds/acre x \$0.390 = \$15.41
P_20_5 = 10.5 pounds/acre x \$0.476 = \$5.00
K_20 = 57.2 pounds/acre x \$0.358 = \$20.48
Corn Stover Nutrient Value: \$40.89

Average 2012 corn yield of 122.0 bushels per acre produce 5,807 pounds or 2.90 tons of corn stover per acre. Corn stover nutrient values per unit ($40.89) divided by the tons produced per acre (2.90) yields a $14.10 per ton nutrient value. Per ton nutrient values will be converted to per acre nutrient valued based on reported recovery rates of 35 percent (Petrolia (2009) was estimated to be $14.31 per acre ($40.89 x .35 = $14.31).

While the nutrient value of corn stover was $40.89 per unit compared to $36.54 per unit for wheat straw, the per acre nutrient value was very similar, $14.31 for corn stover and $15.71 for wheat straw. Even though more biomass is produced on an acre of corn than an acre of wheat straw, the nutrient value per acre is very similar. This would suggest that the value of the biomass to the farmer would not vary greatly from wheat straw to corn stover.

4.5.6.3 Baling

Previous research suggests producers in North Dakota are unlikely to own the required equipment, nor have the available labor or inclination to bale, load or transport biomass. While some producers may be willing to do one or all those processes, it was assumed for this analysis that biomass gathering and transportation activities would be done by custom operators. Large square and round bales are the most common bales type in North Dakota. Accordingly, custom rates per ton were based on average custom rates for large round and square bales.. Custom baling rates per ton for wheat straw and corn stover were reported by Aakre (2014a) as follows:

Table 42. Custom Baling Rates, North Dakota, 2013

	Range	Mode	Average
	----------------------------$ per bale	------------------------------	
Large square bale (700#)	3.00 – 20.00	n/a	9.64
Large round bales (1,500 # or less)	3.00-30.00	10.00	9.47
Large round bales (over 1,500 #)	2.50-22.00	10.00	10.53

Average baling cost per ton were calculated as follows

Large square bales:

$$\frac{2{,}000 \text{ pounds}}{700 \text{ pounds per bale}} = 2.86 \text{ bales per ton}$$

2.86 bales/ton x $9.64/bale = $27.57 per ton

Round bales:

$$\frac{2{,}000 \text{ pounds}}{1{,}000 \text{ pounds per bale}} = 2.0 \text{ bales per ton}$$

2.0 bales per ton x $9.47/bale = $18.94 per ton

Average cost per ton = $23.26 per ton

Baling costs per acre for wheat straw take into account the recoverable straw harvested. Using the 2012 per acre wheat yield of 43.7 bushels per acre, 3,732 pounds of straw per acre would be produced. Recoverable straw for this yield would be:

Recoverable straw (pounds) = total straw (pounds) x recovery rate (percent)
Recoverable straw (pounds) = 3,732 pounds x 0.43
Recoverable straw (pounds) = 1,600 pounds per acre

For 700# bales = 1,600 pounds straw ÷ 700 pounds = 2.3 bales/acre
For 1000# bales = 1,600 pounds straw ÷ 1,000 pounds = 1.6 bales/acre

Average per acre baling cost = 2.3 square bales x $9.64 = $22.17
Average per acre baling cost = 1.6 round bales x $9.47 = $15.15
Average baling cost per acre = ($22.17 + $15.15) ÷2 = $18.66

Baling costs for corn stover include costs for mowing and raking the stover into windrows. The average custom rate for mowing was $8.85 per acre and for raking was $5.57 per acre (Aakre 2014a). Per acre custom rates for mowing and raking corn stover can be converted to per ton costs. The 122.0 bushel per acre corn yield in 2012 produced 5,807pounds of corn stover. Recoverable stover is 35 percent of the total produced, or 2,032 pounds per acre. This results in 1.0163 tons of stover (2,032 pounds of stover divided by 2,000 pounds in a ton equals 1.0163 tons per acre). The per ton calculation would be:

Mowing cost per ton = custom rate per acre ÷ tons per acre
Mowing cost per ton = $8.85 ÷ 1.0163
Mowing cost per ton = $8.71

Raking cost per ton = custom rate per acre ÷ tons per acre
Raking cost per ton = $5.57 ÷ 1.0163
Raking cost per ton = $5.48

Baling costs per acre for corn stover were based on the 2012 yield of 122.0 bushel per acre yield that produced 5,807 pounds of corn stover. Recoverable stover rates were 35 percent. Pounds of recoverable stover for this yield would be:

Recoverable stover per acre (pounds) = total stover per acre (pounds) x recovery rate
Recoverable stover per acre (pounds) = 5,807 pounds x 0.35
Recoverable stover per acre (pounds) = 2,032 pounds per acre

700# square bales: 2,032 pounds stover / 700 = 2.9 bales/acre
1000# round bales: 2,032 pounds stover / 1000 = 2.0 bales/acre

Per acre cost for 700# square bale = 2.9 square bales x $9.64 per bale = $27.96
Per acre cost for 1,000# round bale= 2.0 round bales x $9.47 per bale = $18.94
Per acre sverage cost per bale = (27.96 + 18.94) / 2 = $23.45

Total cost per acre corn stover:

mowing = $8.85
raking = $5.57
baling = $23.45
Total $37.87

Total cost per ton corn stover baling:

mowing = $8.71
raking = $5.48
baling = $23.26
Total $37.45

The two extra operations and the greater number of pounds per acre of biomass result in a much higher per acre cost for corn stover than for wheat straw. In the future it is possible the mowing and raking operations would be streamlined with shredding corn heads or other mechanical operations that could windrow the stover during the harvest operation. New technology to perform gathering of corn stover during harvesting is not in use in North Dakota at this time.

4.5.6.4 Collection and Loading

Bales must be moved off the field and transferred either to the depot or stored at an intermediate location like the edge of the field until bales are transported to the depot. Bales will need to be moved off the field after baling to allow operators to complete post-harvest field work. Bale collection and loading operations are based on custom work rates (Aakre 2014a).

Multiple bale collection machinery is not common in North Dakota. If the demand for biomass were such to warrant multiple bale collection systems, bale collection costs could possibly be less in the future. Bale collection and loading operations are based on custom work rates and the following assumptions (Aakre 2014a):

- tractor loader charged at $60 per hour (Aakre 2014a)
- 2 bales per trip
- average round trip to haul bales to a storage location was one-half mile
- 12 trips per hour or 24 bales per hour (assume tractor loader speed of 6mph)
- cost per bale $2.50 ($60/hour ÷ 24 bales per hour = $2.50)
- average bale weight 850 pounds (average of 700 pound square and 1,000 pound round bales)

The cost per ton for collecting wheat straw and corn stover was the same, because the process was the same regardless of type of biomass. Cost per acre for collection of corn stover was higher than for wheat straw because per acres biomass production is greater for corn stover than for wheat straw.

The cost per ton for collecting either wheat straw or corn stover was estimated to be:

$$\text{Bales per ton} = \frac{\text{1,600.4 pounds}}{\text{850 pounds}} = 2.35$$

$$\text{Cost per ton} = \text{2.35 bales per ton x \$2.50 per ton} = \$5.88$$

Per acre cost of collecting wheat straw bales:

Bales per acre = $\frac{\text{Recoverable Straw in Pounds}}{\text{bale size in pounds}}$

Bales per acre = $\frac{\text{1,600 pounds}}{\text{850 pounds}}$

Bales per acre = 1.88 bales per acre

Cost per Acre = 1.88 bale/acre x $2.50/bale

Wheat Straw Collection = $4.70 per acre

Per acre cost of collection corn stover bale:

Bales per acre = $\frac{\text{Recoverable Straw in Pounds}}{\text{bale size in pounds}}$

Bales per acre = $\frac{\text{2,032 pounds}}{\text{850 pounds}}$

Bales per acre = 2.39 bales per acre

Cost per acre = 2.39 bale/acre x $2.50/bale

Cost per acre = $5.98 per acre

Using the same custom rate as for collection ($60.00 per hour), a per bale charge of $1.00 per bale was estimated for loading. Per ton loading charges are the same for both wheat straw and corn stover. A semi could haul 54 – 700 pound square bales, or 30 – 1,000 pound round bales. The average number of bales was 42 per load and the average load was 16.95 tons. Cost per ton for loading wheat straw or corn stover was:

Loading cost per ton = $\frac{\text{42.00 bales per truckload x \$1 per bale}}{\text{16.95 tons per load}}$

Loading cost per ton = $2.47 per ton

Per acre cost of loading wheat straw bales, and corn stover bales was different because of the greater amount of biomass per acre from corn. These calculations were as follows:

Bales per acre = $\frac{\text{Recoverable Biomass in pounds}}{\text{bale size in pounds}}$ x loading cost

Bale loading cost per acre for wheat straw = $\frac{\text{1,600 pounds}}{\text{850 pounds}}$ x \$1.00 per bale

Bale loading cost per acre for wheat straw = 1.88 bales per acre

Bale loading cost per acre for corn stover = $\frac{\text{2,032 pounds}}{\text{850 pounds}}$ x \$1.00 per bale

Bale loading cost per acre for corn stover = 2.39 bales per acre x \$1.00 per bale

Bale loading cost per acre for corn stover = \$2.39 per acre

4.5.6.5 Transportation

Transportation costs were based on cost associated with the two most common types of bales in North Dakota, 700 pound square bales and 1,000 pound round bales. Based on published custom rates and personal conversation with North Dakota State University Extension farm management economist (Aakre 2014a; Aakre 2014b) cost for hauling straw with a semi-truck and flatbed trailer was estimated to be \$4.00 per loaded mile. The average cost per ton per loaded mile was calculated as follows:

> A semi loaded with large round bales could haul 30 bales, or 15 tons (30 - 1,000 pound bales is 30,000 pounds or 15 tons).
>
> A semi loaded with large square bales could haul 54 bales, or 18.9 tons (54 - 700 pound bales is 37,800 pounds or 18.9 tons).
>
> Large round bale = \$4.00/mile ÷ 15 tons = \$0.27 / ton / loaded mile
>
> Large square bales = \$4.00/mile ÷ 18.9 tons = \$0 .21 / ton / loaded mile
>
> Average cost per ton loaded mile = \$0.27/ton/loaded mile
> + \$<u>0.21/ton/loaded mile</u>
> \$0.48 ÷ 2 = \$0.24/loaded mile
>
> Average cost per ton per loaded mile = \$0.24 per ton per loaded mile

One AFEX pelleting depot would need 38,500 tons of biomass per year to operate at full capacity. An average loaded mile haul distance was determined as follows:

38,500 tons per year = 77,000,000 pounds of biomass
North Dakota average wheat yield for 2006-2012 is 36.1 bushels per acre

36.1 bushels per acre produces 3,075 pounds of straw
3,074.6 pounds of straw x .43 = 1,322 pounds of recoverable straw per acre

77,000,000 pounds of biomass ÷ 1,322 pounds recoverable per acre = 58,245 acres

Assuming 50 percent of acreage in wheat and corn, 116,490 acres could supply needed biomass. However it is unlikely that all available biomass could be secured for collection. Assuming only 40 percent of wheat and corn acres could be secured for biomass collection, an 175,00 acres or 291,225 acres total would be needed to supply a 110 ton per day AFEX pretreatment biomass depot.

A 12.5 mile radius from a depot would provide 314,000 acres

12.5 miles = 66,000 feet
$a = \pi r^2 a = (66{,}000)^2 \times 3.14$
a = 13,677,840,000 sq ft
1 acre = 43,566 sq ft

$$\text{total acres} = \frac{13{,}677{,}840{,}000}{43{,}560} = 314{,}600 \text{ acres}$$

If the pelleting depot was centrally located with respect to biomass production, one-half of the travel radius (12.5 miles) would be the average haul distance. However, roads do not go directly to collection points and it is not likely that the depot would be perfectly centrally located or that hualing distance would be perfectly maximized. Accordingly a hauling distance of 10.0 miles was used for this analysis. If the wheat yields were greater than the 2000-2012 average (36.1 bushels per acre), the average travel distance could be reduced. Likewise, if the wheat yields were less than the average, the average travel distance could be greater than 10.0 miles. Based on an average loaded mile travel distance of 10.0 miles, the delivered cost per ton would be:

Wheat straw transportation cost per ton = 10.0 miles x $.24/ton/loaded mile
Wheat straw transportation cost per ton = $2.40/ton

Using the 2012 wheat yield of 43.7 bushels per acre 3,722 pounds of straw was produced, resulting in 1,600 pounds of recoverable straw. Based on the 2012 crop per acre wheat straw transportation costs per acre would be:

Wheat straw transportation cost per acre = 1,600 pounds/acre ÷ 2,000 pound/ton x \$2.40/ton
Wheat straw transportation cost per acre = .8002 tons/acre x \$2.40/ton
Wheat straw transportation cost per acre = \$1.92/acre

Transportation costs per acre would be higher for corn stover because more pounds of biomass are produced per acre. Corn yields for 2012 were of 122.0 bushels per acre which produced 5,807pounds of corn stover, with 2,035 pounds recoverable. Per acre cost of transportation for corn stover would be:

Corn stover transportation cost per acre = 2,032.5 pounds/acre ÷ 2,000 pounds/ton x \$2.40/ton
Corn stover transportation cost per acre = 1.02 tons/acre x \$2.40/ton
Corn stover transportation cost per acre = \$2.45/acre

Because the haul distract was assumed to be quite small, the transportation costs would be rather low, less than baling costs. Naturally transportation costs could vary based on the distances hauled.

4.5.6.6 Grower Incentive

To encourage farmer participation a \$5.00 per ton incentive was added to the biomass procurement budgets (Cenusa Bioengery 2012). Per ton incentive costs were converted to per acre values as follows:

Wheat straw yields of 43.7 bushels per acre in 2012 bushels per acre produced 3,372 pounds of biomass and 1,600 pounds of recoverable straw. Per acre farmer incentive for wheat straw was calculated as follows:

Recoverable straw per acre = 1,600 pounds ÷ 2,000 pounds/ton
Recoverable straw per acre = 0.8002 tons/acre
Cost per acre for incentive = \$5.00/ton x 0.8002 tons/acre
Cost per acre for incentive = \$4.00/acre for wheat straw

Corn yields of 122 bushels per acres for 2012 produced 5,807 pounds of corn stover or 2,032 pounds of recoverable corn stover. Per acre farmer incentive for wheat straw was calculated as follows:

Recoverable corn stover = 2,032.5 pounds ÷ 2,000 pounds/ton
Recoverable corn stover = 1.02 tons/acre
Cost per acre for incentive = \$5.00/ton x 1.02 tons per acre
Cost per acre for incentive = \$5.10/acre for corn stover

Converting the per ton incentive payment to a per acre value facilitates incorporating incentive payments in to producer budgets.

4.5.6.7 Total Biomass Costs

Total costs to gather, bale, load and transport wheat straw and corn stover to an AFEX pelleting depot are presented in Table 43. Costs for wheat straw are based on the nutrient value of the biomass, baling, loading and the transportation costs and a producer incentive payment. Costs for corn stover were also based on the nutrient value of the stover, baling, loading and transportation cost, and a producer incentive, but also included an additional cost for mowing and raking the stover into windrows. The cost per ton for wheat straw was estimated to be \$58.66 per ton and the cost per ton for corn stover was estimated to be \$67.30 per ton (Table 43). Cost per acre for wheat straw was estimated to be \$46.87 and \$68.10 for corn stover.

Table 43. Costs Per Ton and Per Acre for Purchase, Collection, and Transportation of Wheat Straw and Corn Stover to an AFEX Pelleting Depot, 2013

	Wheat Straw		Corn Stover	
Item	per acre	per ton	per acre	per ton
	------------dollars----------		-----------dollars-----------	
Farmer Incentive	4.00	5.00	5.10	5.00
Nutrient Value	15.71	19.65	14.31	14.10
Mowing	- -	- -	8.85	8.71
Raking	- -	- -	5.57	5.48
Baling	18.66	22.26	23.45	22.26
Bale Collection	4.70	5.88	5.98	5.88
Bale Loading	1.88	2.47	2.39	2.47
Trucking	1.92	2.40	2.45	2.40
Total	46.87	57.66	68.10	66.30

4.6 Potential Markets: Livestock Industry, North Dakota

While the assessment of potential available biomass clearly demonstrates sufficient supply of biomass to support many AFEX pretreatment depots, demand for pretreated biomass will likely drive development. One likely initial market for AFEX treated biomass is ruminant livestock feed. This section will provide a brief assessment of potential demand for AFEX pre-treated biomass as feed in backgrounding and finishing lots in North Dakota.

In 2014, North Dakota ranked 9th in the nation for total beef cow numbers with nearly 943,000 head (NASS 2014). Total North Dakota cattle numbers reported in January of 2014 were nearly 1.8 million. However, North Dakota's beef industry is primary comprised of cow calf production. Cow calf production is characterized by producers that market spring born calves in the fall rather than retaining them to finished weights before marketing. NASS (2014) reported the North Dakota calf crop at 820, 000 head. While most of the calves produced in North Dakota are fed to finished weights in other states, some producers background cattle in place and there are some finish feeding lots in North Dakota. Both backgrounding and fed cattle operations would represent a represent a potential market for AFEX pretreated biomass. Preliminary feeding trails have suggested that AFEX pretreated biomass can be substituted in feeding rations with no significant difference in weight gain.

The state's feedlot capacity provided some insight into the size of an initial potential market for AFEX treated biomass. The most recent feedlot study was conducted in January of 2008. NASS surveyed producers in North Dakota to estimate the state's feedlot capacity and number of cattle fed annually. Feedlot capacity and number of head fed annually was reported by NASS Crop Reporting Districts and is detailed in Table 44

Table 44. Feedlots and Cattle on Feed by Crop Reporting District, North Dakota, January 1, 2008

	Number of feedlots	Feedlot capacity	Cattle on feed	Cattle finished annually
Northwest	n/a	n/a	n/a	n/a
North Central	14	18,300	8,900	4,500
Northeast	8	10,000	7,400	11,800
West Central	27	42,900	18,200	11,900
Central	16	22,400	9,200	9,600
East Central	n/a	n/a	n/a	n/a
Southwest	26	45,000	35,100	29,800
South Central	12	24,100	15,600	9,100
South East	41	54,800	34,800	19,000
Combined Districts[1]	7	8,800	4,800	7,000
Total	151	226,300	134,000	102,700

[1] District where insufficient observations were collected to report separately to avoid potential disclosure issues were combined, namely the Northwest and East Central Districts.

While 102, 700 head were finished and sent directly to slaughter, 241,000 cattle were fed in North Dakota in 2007 (NASS 2008) (data not shown). This includes finished cattle sent directly to slaughter and cattle backgrounded. Total fed cattle was not reported by crop reporting district.

Estimates of cattle on feed included only feedlots with a capacity of 500 head or more. An estimate of the number of cattle backgrounded or fed to finishing at feedlots smaller than 500 head was not available. Most finish feedlots in the state are over 500 head so most finishing operations would be captured by the survey report Petry (2014) However, cow calf producers often background on site on their farm or ranch. Hodur et al. (2007) reported 61 percent of ranchers in ND retain calves after weaning on ranch for 1 to 6 months. No secondary data or estimates of the number of head backgrounded on site in North Dakota was available. Further numbers can vary greatly from year to year based on any number of market or environmental conditions such as drought, high feed costs, market instability, high spring calf prices, low spring calf prices, etc. Producers' decisions to background can vary from year to year (Hodur et al. 2007, Petry 2014). Cattle backgrounded on site and in smaller lots represent a potential market for AFEX pretreated biomass, but an estimate of the size of that market is beyond the scope of this study.

Preliminary feeding trials suggest that AFEX pretreated biomass could be substituted for corn and achieve equivalent weight gain and carcass quality. Preliminary animal trails fed 28 pounds of dry matter per day with a 30 percent substitution of AFEX treated biomass in the treatment group. A thirty percent substitution was equal to 8.4 pounds of AFEX pretreated biomass per day. Using a substitute rate of 8.4 pounds per day and the number of cattle on feed in the state, an estimate of the number of depots needed to supply the state's current livestock feeding and finishing industry can be approximated.

A single 110 ton AFEX pretreatment facility produces 220,000 pound per day. With a daily ration of 8.2 pounds per day, a single AFEX pretreatment facility could feed 26,190 head per day. Based on the number of fed cattle in the last year data is available (2007), ten 110-tons per day AFEX pretreatment plants could provide sufficient feed for 241,000 head of fed cattle.

Adequate biomass is available to support an AFEX depot in almost any area of the state. However, it would be advantageous to locate near where the cattle industry is concentrated. Cattle feeding operations are more prevalent in the southern tier and southwest North Dakota. Although AFEX pre-treated biomass pellets can be easily shipped (the pellets are of similar density as corn and can be handled with currently available grain handling equipment), feasibility of shipping would be contingent on the relative value of the AFEX pre-treated pellets compared to corn.

This assessment of the potential livestock market in North Dakota is not sufficient for nor intended to represent a feasibility study for potential livestock market in North Dakota. Recent trend indicate the number of fed cattle in the state is declining, but the number of cattle backgrounded increasing (Petry 2014). That trend may be advantageous as producers in North Dakota are accustomed to feeding a wide variety of feedstocks, such as wheat mids, sugarbeet tailings, and DDGs from ethanol production and futher study is needed to quantify market potential (Petry 2014). Rather, it represents a very preliminary assessment of potential market opportunities. Findings from preliminary feeding trials and additional study examining nutritional and cost analysis of various feeding rations is needed to further assess market potential. This preliminary assessment of potential market opportunities also allows for assessment of the regional economic effects of a system of AFEX pre-treatment depots. Economic effects are detailed in the following section.

4.7 Economic Impact

Three regional economic impact scenarios were examined: a 110-ton per day AFEX depot, a 220-ton per day plant, and a 10 110-tons per day depot system. The ten plant depot system is based on the estimate of the potential market for AFEX pretreated biomass in the state's cattle feeding industry.

An AFEX depot is not a large scale development, with an estimated cost of $9.7 million. These plants could be a cooperative effort between a grain farmer and a livestock producer, a joint venture with a local elevator, or an entrepreneurial opportunity. Unlike a biorefinery, an individual AFEX plant is not such a large undertaking that it would require a large corporate structure to be built and operated. Because the capital investment and operating costs are not large, the economic impact is also smaller. An economic impact analysis will provide an indication of the economic effects an AFEX depot would provide a local community.

For this analysis, three separate levels of development will be considered. The impacts for a single 110-tons per day AFEX depot will be estimated, as will those for a single 220-tons per day plant, and a potential industry of 10 depots each with a 110-tons per day capacity. Impacts for these three scenarios will be presented separately. Also, the construction phase and the operational phase economic impacts will be presented separately. Impacts for the 10-depot industry were based on 10 times those for a single 110-tons per day plant.

An economic contribution assessment measures the changes in economic variables that result from in-state expenditure by a given industry. An economic impact analysis represents an estimate of all relevant in-state expenditures and returns associated with an industry, activity, or project. The economic impact approach has been used for assessments of industries, activities, and projects in North Dakota (Bangsund and Hodur 2013a; Bangsund and Leistritz 1995, 2005, 2009, 2010; Bangsund et al. 2012; Coon et al. 2012a, 2012b, 2012c; Hodur et al. 2006; Hodur and Leistritz 2007).

Economic activity of a project, program, policy, or activity can be categorized into direct and secondary impacts. Direct impacts are those changes in output, employment, or income that represent the initial or first-round effects of the project, program, policy, or activity. Secondary impacts (sometimes further categorized into indirect and induced effects) result from subsequent rounds of spending and re-spending within the economy. This process of spending and re-spending is sometimes termed the multiplier process, and the resultant secondary effects are sometimes referred to as multiplier effects (Leistritz and Murdock 1981).

Input-Output (I-O) analysis is an economic tool that traces linkages among sectors of an economy and calculates the total business activity resulting from a direct impact in a basic sector (Coon et al. 1985). The ND I-O Model has 17 economic sectors, is closed with respect to households (households are included in the model), and was developed from primary (survey) data from firms and households in North Dakota. The ND I-O Model consists of interdependence coefficients, or multipliers, that measure the level of business activity generated in each economic sector from an additional dollar of expenditures in a given sector. A sector is a group of similar economic units, (e.g., firms engaged in retail trade make up the

Retail Trade Sector). For a complete description of the input-output model, see Coon et al. (1985).

Empirical testing has shown the North Dakota Input-Output Model is sufficiently accurate in estimating gross business volume, personal income, retail trade activity, and gross receipts in major economic sectors in North Dakota. Over the period 1958-2011, estimates of statewide personal income averaged within 10 percent of comparable values reported by the U. S. Department of Commerce (Coon et al. 2013; Bureau of Economic Analysis 2013). Coon et al. (2013) measured the statistical differences between the estimates of personal income from the two sources and found the absolute average difference was 7.0 percent, mean difference was -4.63 percent, and Theil's coefficient was 0.0400 for the 1958-2011 period.

4.7.1 Construction Impacts

Detailed construction expenditures for a 110-tons per day and a 220-tons per day AFEX depot were detailed earlier in the report. These expenditures were allocated to appropriate North Dakota Input-Output Model sectors based on the Standard Industrial Classification Manual (Office of Management and Budget 1972). Various expenditures were allocated to the following sectors: Construction expenditures were allocated to the Construction; Agricultural Processing and Miscellaneous Manufacturing; Retail Trade; Business and Personal Services; and Households Sectors. Construction budgets for equipment and activities were divided into expenditures made in state to North Dakota entities versus expenditures made to out of state entities. Expenditures for specialized AFEX equipment such as AFEX reactors and compressors would most likely be made to out-of-state companies that fabricate that type of equipment. Other less specialize equipment such as pelletizers, holding tanks and equipment for handling biomass were assumed to be available from in-state firms. Of the total estimated AFEX depot construction cost of $9.7 million for a 110-tons per day plant, an estimates $3.8 million would accrue in-state. Construction costs for s 220-tons per day depot were estimated to be $18.5 million of which $7.3 million of the expenditures would accrue to North Dakota entities. Estimated in-state capital expenditures for construction of a 110-tons per day AFEX depot, a 220-tons per day AFEX depot, and a 10-depot industry are detailed in Table 45.

Table 45. In-state Capital Expenditures by Economic Sector for Construction of AFEX Pelleting Depots, North Dakota

Sector	110-Tons Per Day Depot	220-Tons Per Day Depot	10-Depot Industry[1]
	---------------------------- $000	------------------------	
Construction	985	1,942	9,847
Ag Processing & Misc. Manufacturing	233	352	2,327
Retail Trade	1,680	3,308	16,801
Professional & Social Services	251	380	2,508
Households	679	1,359	6,795
TOTAL	3,828	7,341	38,278

[1] Based on North Dakota cattle numbers the industry could potentially support 10 depots with a 110-tons per day capacity.

Direct construction economic impacts

Local expenditures for construction of an AFEX depot comprise the direct economic impact, or the first-round effects on the state's economy. Construction effects are one time impacts associated with construction activities. Construction effects for the 10 depot industry would likely accrue over the course of several to many years, depending on time associated with build out. Effects of a single 110 or 220 tonsper day depot would accrue over a 12-month period.

In-state expenditures for construction of a 110-tons per day AFEX depot were estimated to be $3.8 million. Expenditures to the Retail Sector totaled $1.7 million followed by the Construction Sector with $1.0 million and the Households Sector $0.7 million. In-state expenditures were roughly 40 percent of total expenditures as specialized equipment likely purchased from specialized out of state firms comprises a significant part of the total project cost. In state effects were similar for a 220-tons per day AFEX depot. In-state expenditures related to construction would total $7.3 million. Like the smaller depot the greatest level of expenditures was in the Retail Trade Sector ($3.3 million), followed by the Construction Sector ($1.9 million) and the Households Sector ($1.4 million). There are some economies of size for the construction of a 220-tons per day plant, as it is slightly less expensive than building 2 of the 110-tons per day depots. Construction expenditures for a 10-depot AFEX pelleting industry (110-tons per day plants) were obtained by multiplying the expenditures for a single 110-tons per day depot by 10. Total in-state expenditures associated with the build-out of a 10 depot system totaled nearly 38.3 million.

Construction Sector expenditures included building construction, raw material and pellet storage facilities. The Agricultural Processing and Miscellaneous Manufacturing Sector included expenditures for holding tanks, pelletizer, and rotary drum dryers that could be fabricated in North Dakota. Expenditures for bale handling equipment, tub grinder, hammer mill conveyors, and miscellaneous equipment were allocated to the Retail Trade Sector. Outlays for installation of specialized and general equipment were allocated to the Business and Personal Services Sector. Expenditures for land for buildings and storage were allocated to the Households Sector.

Total construction economic impacts

Inputting AFEX depot construction expenditures to the North Dakota Input-Output Model estimated total construction phase economic impacts. Total economic impacts are the result of direct (construction expenditures) and secondary effects which result from the spending and re-spending of the original dollars added to the economy. The spending and re-spending of the original dollar is known as the multiplier process.

The economic impacts for construction of a 110-ton per day AFEX depot, a 220-ton per day AFEX depot, and a 10-depot industry are presented in Table 46. Business activity as a result of the construction of a 110-ton per day depot was $9.7 million. The most activity was in the Retail Trade Sector with $3.3 million in expenditures followed by the Households Sector with $2.7 million. Increased business activity in the Households Sector represents personal income. Increased business activity in the Construction Sector was $1.2 million. Construction of a A 20-tons per day AFEX depot would result in $18.2 million in additional business activity. Activity in the Retail Trade Sector would increase by $6.4 million and activity in the Households Sector (personal income) would increase by $5.2 million. Business activity would increase by $2.3 million in the Construction Sector.

Total business activity attributed to that construction of a 10 110-ton per day depots would be $97.2 million. While the economic impact associated with the construction of a 110-tons per day or a 220-tons per day depot would likely occur in a one-year period, the 10-depot industry would likely take place over many years. To compare the economic impacts for an individual depot to the industry total, time frame associated with construction must be considered. A 10-depot industry would result in increased retail trade activity of $33.0 million, increased personal income of $26.9 million, and increased business volume of $11.8 million in the Construction Sector.

Increased economic activity associated with the construction of an AFEX depot would also produce increased tax revenues. Sales and use tax collections resulting from increased retail trade activity would be $153,000 for a 110-tons per day depot, and $297,000 for a 220-tons per day depot. A 10-depot industry would generate enough retail trade to produce $1.5 million in sales and use tax revenue. The 110-tons per day and 220-tons per day depots would generate enough personal income to create tax collections of $40,000 and $78,000, respectively. Personal income tax collections for a 10-depot industry would amount to $404,000. Construction of a 110-tons per day depot, a 220-tons per day depot, and a 10-depot industry would generate enough business activity to create corporate income tax collections of $212,000, $412,000, and $2,219,000, respectively.

Table 46. Total Economic Impact for Construction of a 110-Tons Per Day Depot, a 220-Tons Per Day Depot, and a 10-Facility Industry, AFEX Pelleting Depots, North Dakota

Item	110-Tons Per Day Depot	220-Tons Per Day Depot	10-Depot Industry[1]
	($000)		
Total Impact:			
Construction	1,182	2,319	11,817
Communications & Public Util	266	505	2,656
Ag Proc & Misc Mfg	536	868	5,355
Retail Trade	3,305	6,408	33,049
Fin, Ins, Real Est	352	670	3,515
Bus & Pers Serv	378	620	3,775
Pro & Soc Serv	177	340	1,775
Households	2,694	5,175	26,946
Other[2]	831	1,525	8,313
TOTAL	9,721	18,249	97,201
Tax Revenues:			
Sales & Use	153	297	1,530
Personal Income	40	78	404
Corporate Income	19	37	195
TOTAL	212	412	2,129
Employment:	(jobs)		
Direct (Peak FTE)	N/A	N/A	N/A
Secondary (FTE)	19	34	191
TOTAL			

[1] Other Includes agriculture, mining, transportation, and government.

[2] Based on North Dakota cattle numbers the industry could potentially support 10 depots with a capacity of 110-tons per day.

Estimates were not available for the AFEX depot construction direct workforce. Secondary (indirect and induced) employment related to construction expenditures for a 110-tons per day depot would support 19 jobs, and a 220 tons per day deport would support 34 jobs. Secondary employment related to the 10 depot industry would support 191 jobs. Secondary employment figures should be viewed with caution.

Because of model assumptions, estimates of secondary employment are likely inflated, especially during brief periods of construction for smaller scale construction activities like an AFEX depot. Input-output models assume that all sectors are at full employment and that an increase in business volume in a basic sector (activities associated with construction of an AFEX depot) translates directly into an increase in business volume in non-basic sectors and households (wages/salaries). Further, any increase in business volume would translate into an increase in labor requirements to meet additional demand. However, if the increase in business volume does not exceed the capacity of the current labor force no increase in labor (new jobs) would be needed to meet the additional demand. It is likely that the existing labor force would have been able to absorb any addition demand related to construction activities of an AFEX depot. This would be true for either the 110 tons per day, the 220-tons per day or 10 depot industry. Even though construction activity related to the 10 depot industry is substantially larger, construction activity will likely take place over multiple years.

Recent research on secondary workers in North Dakota's oil patch found that secondary jobs did not materialize as economic theory would suggest (Bangsund and Hodur 2012, Coon et al. 2012) which supports using secondary employment figures with caution. Infrastructure limitations, housing shortages, businesses unwillingness to add employees for a short-term boom, technology advances, labor efficiencies, and competition for workers by other industries, all contribute to less secondary employment. Rapid growth can lead to crowding out effects (Macke and Gardner 2012). It is likely that the existing labor force would have absorbed the demand associated construction of an AFEX depot or depots.

4.7.2 Operational Impacts

Expenditures related to operations represent annual direct economic effects as compared to the one-time effects associated with depot construction. Direct economic impacts for operation of a 110-tons per day AFEX depot, a 220-tons per day depot, and a 10-depot industry are presented in Table 47. These expenditures represent payments to North Dakota entities. Payments made to out-of-state entities are considered economic leakages and are excluded from the economic impact analysis. For an AFEX pelleting depot, nearly all of the operational expenditures accrue in North Dakota and to North Dakota entities Operational expenditures were determined from budgets detailed earlier in the report. Based on budget expenditure categories, all operational expenses were assumed to be made in North Dakota.

Direct operational impacts

Inputs to production; wheat straw, corn stover, natural gas, ammonia, electricity, water, and labor are available in North Dakota. Expenditures for inputs to production were allocated to the appropriate economic sector: Communications and Public Utilities; Transportation; Retail Trade; Finance, Insurance and Real Estate; Business and Personal Services; and Households.

Wages and salaries, payment to farmers for biomass represent payments to the Households sector. Payments for custom rate biomass collection (baling, collecting bales, loading bales, etc.) were allocated to the Business and Personal Services Sector, while freight to transport the biomass bales to the AFEX depot were include in the Transportation Sector. Payments to households and biomass collection reflected price differences for wheat straw and corn stover. It was assumed that corn stover made up 65 percent of the collected biomass, and wheat straw the remaining 35 percent. Worker benefits were allocated to the Finance, Insurance, and Real Estate Sector and supplies and consumables such as anhydrous ammonia were allocated to the Retail Trade Sector. Expenditures for natural gas, electricity, and water accrued to the Communications and Public Utilities Sectors

Table 47. Estimated In-state Expenditures by Economic Sector for Operations of a 110-Tons Per Day Depot, a 220-Tons Per Day Depot, and a 10-Depot Industry, North Dakota

Sector	110-Tons per Day Depot	220-Tons Per Day Depot	10-depot Industry[1]
	------------------------------	$000	------------------------------
Communications and Public Utilities	773	1,546	7,732
Transportation	97	194	970
Retail Trade	778	1,574	7,780
Finance, Insurance, and Real Estate	159	171	1,586
Business and Personal Services	1,610	3,221	16,102
Households	1,393	2,157	13,928
TOTAL	4,810	8,863	48,098

[1] Based on the number of fed cattle in North Dakota, the cattle industry could potentially support 10 depots with a 110-tons per day capacity.

Total annual operating expenditures for a 110-tons per day depot were estimated to be $4.8 million. Expenditures for Business and Personal Services sector was $1.6 million followed by expenditures to Household of $1.4 million. Expenditures in the Retail Trade Sector and Communications and Public Utilities Sector were similar at $778,000 and $773,000, respectively.

Operational expenditures for a 220-tons per day AFEX depot were $8.9 million annually. The largest outlays were to the Business and Personal Services sector ($3.2 million) followed by the Households sector (3.2 million) and the Communications and Public Utilities Sector ($1.6).

A 10-depot industry would have annual operational expenditures of $48.0 million. Industry expenditures were based on 10 depots with a 110-tons per day capacity, so all operational expenditures would be 10 times those for that sized depot. The industry would annually have expenditures of $13.9 million to the Households Sector, $16.1 million to the Business and Personal Services Sector, $7.8 million to the Retail Trade Sector, and $7,7 million to the Communications and Public Utilities Sector.

Total operational economic impacts

Secondary economic impacts were estimated by applying the coefficients of the North Dakota Input-Output Model to the per sector expenditures to produce estimates of the total annual economic impact for AFEX pelleting depots. Annual impacts will accrue as long as the depots operate. Total economic impacts (direct and secondary) for the 110-tons per day depot, the 220-tons per day depot, and the 10-depot industry are presented in Table48. Total economic impact for a 110-ton per day depot was $13.3 million, a 220-tons per day depot were $24.2 million, and the 10-depot industry was $133 million annually. The 110-tons per day depot would increase the business activity of the Households Sector (personal income) by $4.5 million, and the Retail Trade Sector by $3.2 million annually. The Communications and Public Utilities Sector had business activity increase by $1.2 million, and the Business and personal Services Sector increases by $1.8 million. Operations of the 220-tons per day AFEX depot resulted in an increase of $7.8 million in personal income and $5.9 million in retail trade activity. Business and Personal Services and Communications and Public Utilities Sectors had a $3.6 and $2.4 million increase in business activity, respectively.

An industry comprised of 10 depots with each having a 110-tons per day capacity would generate over $133 million in additional business volume. An AFEX pelleting industry this size would generate $45.1 million in personal income and $32.5 in retail trade activity. The Communications and Public Utilities Sector would generate $12.4 million in new business activity followed by the Business and Personal Services Sector with $18.3 million.

State tax collections associated with the total (direct and secondary) business volumes generated annually would be $244,000 for a 110-tons per day depot, $440,000 for a 220-tons per day depot, and $2.4 million for a 10-depot industry. The 110-tons per day depot would have sales and use tax collections of $151,000, personal income taxes of $68,000, and corporate income taxes of $25,000. Sales and use, personal income, and corporate income tax collections annually for the 220-tons per day depot would be $276,000, $118,000, and $46,000, respectively. A 10-depot industry would generate enough business activity to account for $1.5 million in sales and use taxes, $677,000 in personal income taxes, and $248,000 in corporate income taxes. Property taxes were not analyzed in the report, but would also add revenue to local governments.

A 110-tons per day depot would employ 16 full time equivalent workers direct workers and the business activity generated by the depot's operations would provide 20 secondary (indirect and induced) jobs. The larger 220-tons per day depot is more labor efficient than the smaller depot and requires 20 full time equivalent direct workers. Business activity associated with a 220-tons per ay depot would be expected to support 31 secondary jobs. A ten depot industry would create 160 direct jobs and that level of business activity would be expected to support 211 secondary jobs.

Because of model assumptions, estimates of secondary employment should be viewed with caution. Input-output models assume that all sectors are at full employment and that an increase in business volume in a basic sector (like that associated with AFEX depot operations) translates directly into an increase in business volume in non-basic sectors and households (wages/salaries). Alternatively, any increase in business volume would translate into an increase in labor requirements to meet additional demand. However, if the increase in business volume does not exceed the capacity of the current labor force no increase in labor (new jobs) would be needed to meet the additional demand. It is possible due to model limitations estimates of secondary employment are overstated, especially considering the current robust economy in North Dakota.

Recent research on secondary workers in North Dakota's oil patch found that secondary jobs did not materialize as economic theory would suggest (Bangsund and Hodur 2012, Coon et al. 2012). Infrastructure limitations, housing shortages, businesses unwillingness to add employees for a short-term boom, technology advances, labor efficiencies, and competition for workers by other industries, all contribute to less secondary employment. Rapid growth can lead to crowding out effects (Macke and Gardner 2012). It is likely that the existing labor force would have absorbed the demand associated construction of an AFEX depot or depots.

Table 48. Total Economic Impact for Operations of a 110-Ton Per Day Depot, 220-Ton Per Day Depot, and a 10-Facility Industry Total[1] AFEX Pelleting Depots, North Dakota

Sector	110- tons Per Day Depot	220-Tons Per Day Depot	10-Depot Industry
	($000)		
Total (Direct and Secondary)Impact:			
Construction	308	548	3,076
Communications & Public Utilities	1,246	2,407	12,459
Ag Processing & Misc Manufacturing	164	292	1,637
Retail Trade	3,251	5,957	32,507
Finance, Insurance, Real Estate	734	1,196	7,336
Busisness Personal Services	1,835	3,622	18,350
Professional & Social Services	297	521	2,969
Households	4,511	7,877	45,107
Other[2]	970	1,775	9,707
TOTAL	13,316	24,195	133,148
Tax Revenues:			
Sales and Use	151	276	1,505
Personal Income	68	118	677
Corporate Income	25	46	248
TOTAL	244	440	2,430
Employment: (Jobs)	(number)		
Direct (FTE)	16	20	160
Secondary (FTE)	22	48	287

[1] Based on North Dakota cattle numbers the industry could potentially support 10 depots with a 110-ton per day capacity.

[2] Other includes agriculture, mining, transportation, and government.

While the economic effects are small relative to other industries in North Dakota, depots would be creating new economic activity using biomass that is at this time underutilized. Even though at this time the North Dakota economy is very robust, economic conditions vary regionally. While some regions are growing rapidly other regions in the state are less robust. A system of AFEX pretreatment depots would likely be developed near livestock feeding operations which are concentrated in the southern tier and southwestern North Dakota. Those region's economies are still heavily dependent on agriculture and economic diversification and development is a priority.

4.8 Commercialization

4.8.1 Synopsis

AFEX is a disruptive, transformational technology that has the potential to double worldwide output from existing grain-crop production within the next twenty years. Successful development of AFEX will have a profound impact on our ability to meet growing demand for food, feed, and renewable fuels and chemicals. Building on recent technical success at the laboratory and pilot scale, it is now essential to validate the technology at near commercial scale to enable broad and rapid global deployment.

A major untapped resource is agricultural biomass, the non-edible crop residues such as stalks and leaves that remain after grains are harvested. This biomass constitutes half to two-thirds of the weight of crop material; therefore, about 2 billion to 3 billion tons of biomass are produced every year, of which some must be left in the field to maintain soil quality. Biomass is composed mostly of sugar polymers that are tightly bound and intertwined with an indigestible structural material, lignin. If these sugars could be readily accessed, the biomass could potentially be converted into animal feed and renewable fuels and chemicals. Unlocking the potential of biomass opens up the possibility of capturing an additional 2 billion tons of output from existing agricultural production to supplement global grain output.

We envision that AFEX technology will be implemented at local “depots,” which will receive the raw biomass from farms located within a 5-mile radius. This eliminates the cost of creating expensive transportation networks for low-density raw materials. The AFEX pellets, which have a long shelf life, can be economically stored and shipped from depots to markets using existing grain infrastructure, addressing the second challenge.

AFEX pellets can be used as either a cattle feed ingredient or biorefinery feedstock. In cattle feed applications, the pellets break down in the rumen to release sugars and provide a nutritional energy source similar to that provided currently by grain. For biorefinery feedstock, the pellets are treated with enzymes to release sugars, and the sugars are converted via fermentation into products such as biofuels and bio-based chemicals.

AFEX pellets offer a compelling value in both cattle feed and biorefinery feedstock applications. They offer farmers a lower cost alternative to corn grain and provide biorefineries with much simpler supply logistics and competitive costs compared to other biomass sugar options. The combination of multiple markets, standardized, stable, shippable product, and attractive economics has the potential to make AFEX pellets a tradable, viable biomass commodity, much as grain is today.

4.8.2 The Path Forward

The next critical step, which will build upon these recent successes, is to design, build and operate a 20-100 fold larger demonstration scale depot. A depot of this size is essential to complete the technology development and support necessary large-scale application testing trials for biorefinery applications around the world. In addition, comprehensive animal feeding trials will be necessary to validate the quality of the milk and meat produced and to comply with applicable regulatory requirements. Finally, such a depot will facilitate the development of a simple, robust, turnkey design for commercial depots that will be essential for rapid worldwide rollout of the technology.

MBI is seeking strategic partnerships with a small group of dedicated, like-minded corporate and financial partners to design, build and operate the demonstration depot and participate in the global deployment of the technology. Current estimates for the cost of the first demonstration depot are approximately $20 million of staged capital and operating investment.

Currently, there is no significant large scale production of advanced biofuels in the US. This is due, to a significant degree, the lack of an existing feedstock logistics system to provide a viable feedstock commodity from biomass. MBI plans to build AFEX depots to provide feedstock for the existing animal feed market first to establish an infrastructure that is also suitable to producing AFEX pellets for use in biorefineries to produce both biofuels and chemicals.

This will require MBI to set up channels to market for both licensing the process and manufacturing of the equipment. The clear advantage of the AFEX 3 equipment is the ability to make these units in a factory that will reduce the equipment costs and increase quality. The AFEX 3 units will be transported to a RBPD site for final assembly and installation. MBI's plans are to qualify two to three manufacturers of the AFEX equipment. MBI would license the right to these manufacturers to make and sell the AFEX process equipment. A potential RBPD owner would then have two to three suppliers available to quote on their business. This will drive competition between the equipment suppliers which will lead to further advancements in technology, automation and ease of use.

A RBPD owner will need equipment, but they will also need the rights to run the AFEX process. MBI will license the rights to run the AFEX process directly to the RBPD owners. These could be arranged as cooperative, LLCs or single owner facilities. The low capital costs of the RBPDs will allow for multiple options for financing, which will speed commercialization. MBI will set up standard non-exclusive licensing packages that owners could purchase. Once the owners have the rights to practice the AFEX process and they have obtained equipment from an equipment supplier, they will be ready to start using the AFEX process at their chosen RBPD sites. The ammonia required to run the process will be purchased from a local or national distributor. Ammonia is a commodity chemical that is widely available.
Using more conservative assumptions regarding harvestable biomass that the Harvest Index assessment that calculated a theoretical maximum, preliminary analysis shows that North Dakota could support approximately 50 100 TPD AFEX depots. Table 11 shows the total harvestable biomass for each of the nine regions of North Dakota over the past three years. Values are in US tons of dry biomass per year. The number of depots each region could support is estimated using the lowest biomass value over the past three years.

Assumptions for Table 49 are:

- All data is from USDA Farm Surveys
- Data was collected at the region level
- Data includes corn, winter wheat, spring wheat, and barley
- Assume 1.2 lb of barley straw and wheat straw per pound of grain; 1 lb corn stover per lb grain

- Assume 1 ton barley straw, 1.5 tons wheat straw, and 2 tons corn stover must be left on the field for nutrients or erosion control
- Assume no biomass will be collected if less than 0.5 tons/acre

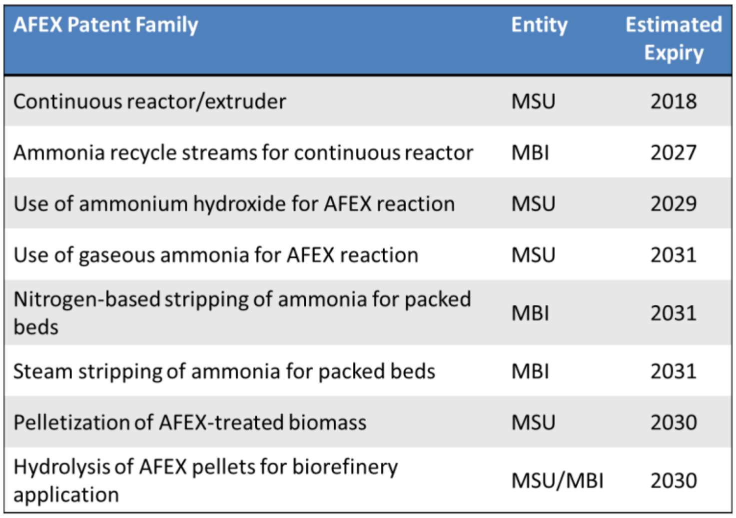
Table 49. North Dakota agricultural residue production by region and potential number of 100 TPD AFEX Depots that could be supported

Region	2010	2011	2012	Average	Number of Depots
North East	398,890	184,832	704,820	429,514	5
East Central	1,385,871	476,483	1,543,396	1,135,250	13
South East	1,284,821	800,930	1,989,383	1,358,378	22
North Central	231,428	60,718	417,134	236,427	1
Central	370,773	267,905	823,986	487,555	7
South Central	119,720	150,374	32,975	101,023	1
North West	134,957	-	303,713	146,224	0
West Central	113,971	42,608	122,893	93,157	1
South West	20,317	-	-	6,772	0
TOTAL	**4,060,748**	**1,983,851**	**5,938,301**	**3,994,300**	**50**

4.8.3 AFEX Intellectual Property and Competitive Advantage

MBI and MSU have a significant portfolio of AFEX patents. This includes over 40 patents and pending patents in eight patent families (Table 12) in 10 countries. The critical base technology patents covering utilization of ammonia gas, ammonia stripping and ammonia recovery and reuse have active lives out to 2031.

Table 50. AFEX Patents



AFEX Patent Family	Entity	Estimated Expiry
Continuous reactor/extruder	MSU	2018
Ammonia recycle streams for continuous reactor	MBI	2027
Use of ammonium hydroxide for AFEX reaction	MSU	2029
Use of gaseous ammonia for AFEX reaction	MSU	2031
Nitrogen-based stripping of ammonia for packed beds	MBI	2031
Steam stripping of ammonia for packed beds	MBI	2031
Pelletization of AFEX-treated biomass	MSU	2030
Hydrolysis of AFEX pellets for biorefinery application	MSU/MBI	2030

5.0 References

Aakre, Dwight. 2014a. *Custom Farm Work Rates in North Dakota Farms, 2013 by North Dakota Farming Regions*. Fargo: North Dakota State University. Extension Service, Farm Management Economist.

Aakre, Dwight. 2014b. *Personal Interview on Transportation Costs for Hay Bales*. Fargo: North Dakota State University, Department of Agribusiness & Applied Economics, Extension Farm Management Economist.

Aden, A. and Foust, T. 2009. Technoeconomic analysis of the dilute sulfuric acid and enzymatic hydrolysis process for the conversion of corn stover to ethanol. Cellulose 16, 535-545.

Alizadeh H, Teymouri F, Gilbert TI, Dale BE. 2005. Pretreatment of switchgrass by ammonia fiber explosion (AFEX). *Appl. Biochem. Biotechnol.* 121–124, 1133–1141.

Bals, Bryan. 2013. Personal Communication. Lansing, Michigan: MBI.

Bals BD, Murnen H, Allen M, Dale BE. 2010. Ammonia fiber expansion (AFEX) treatment of eleven different forages: improvements to fiber digestibility *in vitro. Anim. Feed Sci. Technol.* 155(2–4), 147–155.

Bals, B., C. Gunawan, J. Moore, F. Teymouri, and B.E. Dale. 2014. Enzymatic hydrolysis of pelletized AFEX™-treated corn stover at high solid loading. Biotechnol. Bioeng. 111: 264-271.

Balan, V., Bals, B., Chundawat, S.P.S., Marshall, D., Dale, B.E., 2009. Lignocellulosic biomass pretreatment using AFEX. Methods Mol. Biol. 581, 61-77.

Bangsund, Dean A. and F. Larry Leistritz. 1995 *Economic Contribution of the United States Sunflower Industry*. Agribusiness and Applied Economics Report No. 327. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Bangsund, Dean A. and F. Larry Leistritz. 2005. *Economic Contribution of the Wheat Industry to North Dakota*. Agribusiness and Applied Economics Report No. 554. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Bangsund, Dean A. and F. Larry Leistritz. 2009. *Petroleum Industry's Economic Contribution to North Dakota in 2007*. Agribusiness and Applied Economics Report No. 639. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Bangsund, Dean A. and F. Larry Leistritz. 2010. *Economic Contribution of the Petroleum Industry in North Dakota*. Agribusiness and Applied Economics Report No. 676 & 676-S. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Bangsund, Dean A. and Nancy M. Hodur. 2013a. *Petroleum Industry's Economic Contribution to North Dakota in 2011*. Agribusiness and Applied Economics Report No. 710. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Bangsund, Dean A., Nancy M. Hodur and F. Larry Leistritz. 2012. *Economic Contribution of the Sugarbeet Industry in Minnesota and North Dakota*. Agribusiness and Applied Economics Report No. 688. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Brockema, Sandra. 2009. *Feasibility Study of a biomass Supply for the Spiritwood Industrial Park*. NDIC Contrast No. R001-003. Submitted by Great River Energy, Great Plains Institute, ND Association of Rural Electric Cooperatives, ND Department of Agriculture, ND Farmers Union, and ND Natural Resources Trust.

Bureau of Economic Analysis. 2013. *Personal Income by Major Sources and Earnings by Industry.* Table A05. Internet Website Interactions Tables. www.bea.gov. Washington D.C.: U.S. Department of Commerce.

Campbell, T.J., Teymouri, F., Bals, B., Glassbrook, J., Nielson, C.D., Videto, J., 2013. A packed bed AFEX reactor system for pretreatment of agricultural residues at regional depots. Biofuels 4, in press, DOI 10.4155/BFS.12.71.

Cenusa Bioenergy. 2012. *Sustainable Production and distribution of Bioenergy for the Central USA.* A report to USDA-FIFA AFRI CAP, Grant No. 2011-68005-30411.

Chen, Chengci, Karnes Neill, Dave Wichmann, and Malvern Westcott. 2008. *Hard Red Spring Wheat Response to Row Spacing, Seeding Rate, and Nitrogen.* Agronomy Journal: Volume 100, Issue 5. pp. 296 - 302. Madison, Wisconsin: American Society of Agronomy.

Chevanan, N., A. R. Womac, V. S. Bitra, Igathinathane, C., Mui, P., Yang, Y.T., and S. Sokhansanj. 2010. Bulk density and compaction behavior of knife mill chopped switchgrass, wheat straw and corn stover. Bioresource Technology, 101(1):207-214.

Coon, Randal C., Dean A. Bangsund and Nancy M. Hodur. 2012a. *North Dakota Lignite Energy Industry's Contribution to the State Economy for 2011 and Projected for 2012.* Agribusiness and Applied Economics Staff Paper 12003. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Coon, Randal C., Dean A. Bangsund and Nancy M. Hodur. 2012b. *Economic Impact of the North Dakota University System in 2011.* Agribusiness and Applied Economics Report No. 690. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Coon, Randal C., Dean A. Bangsund and Nancy M. Hodur. 2012c. *Renewable Energy Industries' Contribution to the North Dakota Economy.* Agribusiness and Applied Economics Report No. 702. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Coon, Randal C., Dean A. Bangsund and Nancy M. Hodur. 2013. *North Dakota Input-Output Model Data Base.* Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Coon, Randal C., Dean A. Bangsund and Nancy M. Hodur. 2013a. *The Economic Base of North Dakota in 2011.* AAE Staff Paper 13001. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Coon, Randal C. and F. Larry Leistritz. 2006. *A Potential Role for Wheat Straw in Value-added Agriculture.* Unpublished Report. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Coon, Randal C. and F. Larry Leistritz. 2010. *Nutrient Value of Wheat Straw*. Unpublished Report. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Coon, Randal C., F. Larry Leistritz, Thor A. Hertsgaard, and Arlen G. Leholm. 1985. *The North Dakota Input-Output Model: A Tool for Analyzing Economic Linkages.* Agricultural Economics Report No. 187. Fargo: North Dakota State University, Department of Agricultural Economics.

Dale, BE, B. Ritchie, and D. Marshall. 2011. Patent Application US046525

Dasari, R.K. and Berson, R.E., 2007. The effect of particle size on hydrolysis reaction rates and rheological properties in cellulosic slurries. Appl. Biochem. Biotechnol. 137, 289-299.

Diniz, J.M.B.F, Gil, M.H., Castro, J.A.A.M., 2004. Hornification – its origin and interpretation in wood pulps. Wood Sci. Technol. 37, 489-494.

Eranki, P.L., Bals, B.D., Dale, B.E., 2011. Advanced regional biomass processing depots: A key to the logistical challenges of the cellulosic biofuels industry. Biofuels Bioprod. Bioref. 5, 621-630.

Gao, D., Uppugundla, N., Chundawat, S.P.S., Yu, X., Hermanson, S., Gowda, K., et al., 2011. Hemicellulases and auxiliary enzymes for improved conversion of lignocellulosic biomass to monosaccharides. Biotechnol. Biofuels 4, 5.

Garlock, R.J., Balan, V., Dale, B.E., 2012. Optimization of AFEXTM pretreatment conditions and enzyme mixtures to maximize sugar release from upland and lowland switchgrass. Bioresour. Technol. 104, 757-768.

Goering, H.K., and P.J. Van Soest. 1970. Forage Fiber Analyses (Apparatus, reagents, procedures, and some applications). USDA-ARS Agric. Handbook No. 379. US Govt. Printing Office, Washington, DC. pp. 20.

Gould, Keven. 2007. *Corn Stover Harvesting*. Internet Website: http://beefteam.msu.edu/Resources/Nutrition/CornStoverHarvesting/tabid/595/Default.aspx. Reprint from Cattle Call: Vol 12, Issue 2. East Lansing: Michigan State University Extension Service.

Hanchar RJ, Teymouri F, Nielson CH, McCalla D, Stowers MD. 2007. Separation of glucose and pentose sugars by selective enzyme hydrolysis of AFEX-treated corn fiber. *Appl. Biochem. Biotech*. 136–140(1–12), 313–325.

Hess, J.R., Kenney, K.L., Ovard, L.P., Searcy, E.M., Wright, C.T., 2009. Commodity-scale production of infrastructure-compatible bulk solid from herbaceous lignocellulosic biomass. Idaho National Laboratory, Idaho Falls, INL/EXT-09-17527.

Hess JR, Kenney KL, Park L, Searcy EM, Wright CT. 2009b. *Uniform-Format Solid Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Bulk Solid from Lignocellulosic Biomass.* Idaho National Laboratory, Idaho Falls, ID, USA.

Hodge, D.B., Karim, M.N., Schell, D.J., McMillan, J.D., 2009. Model-based fed-batch for high-solids enzymatic cellulose hydrolysis. Appl. Biochem. Biotechnol. 152, 88-107.

Hodur, Nancy M., F. Larry Leistritz and Tarrand Hertsgaard. 2006. *Contribution of the North Dakota Agricultural Products Utilization Commission Programs to the State Economy.* Agribusiness and Applied Economics Staff Paper 06006. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Hodur, Nancy M. and F. Larry Leistritz. 2007. *The Contribution of North Dakota's Community Pharmacies to the State's Economy.* Agribusiness and Applied Economics Report 597. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Hodur, Nancy M., F. Larry Leistritz, Daniel J. Nudell, Clint Clark, Duane Griffith, Tammie Jensen. 2007. *Northern Great Plains Beef Production: Production and Marketing Practices of Cow-Calf Producers.* Agribusiness and Applied Economics Report 609. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Holtzapple, M. R. Davison, and D. Stuart. 1992. Patent US5171592

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., et al., 2011. Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol. National Renewable Energy Laboratory, NREL Report tp-5100-47764.

Jin, M., Gunawan, C., Balan, V., Lau, M.W., Dale, B.E., 2012. Simultaneous saccharification and co-fermentation (SSCF) of AFEXTM pretreated corn stover for ethanol production using commercial enzymes and Saccharomyces cerevisiae 424A(LNH-ST). Bioresour. Technol. 110, 587-594.

Jones, J.B. 2003. *Agronomic Handbook: Management of Crops, Soils, and their Fertility*. Baco Raton: CRC Press.

Jorgensen, H., Vibe-Pedersen, J., Larsen, J., Felby, C., 2007. Liquefaction of lignocellulose at high-solids concentrations. Biotechnol. Bioeng. 96, 862-870.

Kristensen, J.B., Felby, C., Jorgensen, H., 2009. Yield-determining factors in high-solids enzymatic hydrolysis of lignocellulose. Biotechnol. Biofuels 2, 11.

Laser M, Jin H, Jayawardhana K, Lynd LR. 2009. Coproduction of ethanol and power from switchgrass. *Biofuels Bioprod. Bioref*. 3(2), 195–218.

Leistritz, F. Larry and Steve H. Murdock. 1981. *Socioeconomic Impact of Resource Development: Methods for Assessment*. Westview Press, Boulder Colorado.

Leistritz, F. Larry, Donald M. Senechel, Mark D. Stowers, William F. McDonald, Chris M. Saffron, and Nancy M. Hodur. 2006. *Preliminary Feasibility Analysis for an Integrated Biomaterials and Ethanol* Biorefinery *Using Wheat Straw Feedstock.* AAE Report No. 590. Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Leistritz, F. Larry, Dean A. Bangsund, Nancy M. Hodur and Donald M. Senechal. 2009. “Factors Affecting Agricultural Biomass”. Included in a report to the North Dakota Industrial Commission, “Feasibility Study of a Biomass Supply for the Spiritwood Industrial Park. NDIC Contract No. R001-003, http://www.nd.gov/ndic/renew/projects/r-001-003sp.pdf.

Lundstrom, Darnell. 1994. *Response to Steele County Job Development Authority on Straw Board Growers Questions*. Fargo: North Dakota State University, Extension Service. Agriculture and Natural Resources.

Luo, X.L., Zhu, J.Y., Gleisner, R., Zhan, H.Y., 2011. Effects of wet-pressing-induced fiber hornification on enzymatic saccharification of lignocelluloses. Cellulose 18, 1055-1062.

Kumar, L., Tooyserkani, Z., Sokhansanj, S., Saddler, J.N., 2012. Does densification influence the steam pretreatment and enzymatic hydrolysis of softwoods to sugars? Bioresour. Technol. 121, 190-198.

Mani S, Tabil LG, Sokhansanj S. 2004. Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass. *Biomass Bioenergy* 27(4), 339–352.

Mertens, D.R. 2002. Gravimetric determination of amylase-treated neutral detergent fiber in feeds using refluxing in beakers or crucibles: Collaborative study. J. AOAC Int. 85:1217-1240.

Miao, Z., Shastri, Y., Grift, T.E., Hansen, A.C., Ting, K.C., 2012. Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configurations, and modeling. Biofuels Bioprod. Bioref. 6, 351-362.

Murnen KH, Balan B, Chundawat SH, Bals BD, Costa Sousa L, Dale BE. 2007. Optimization of ammonia fiber expansion (AFEX) pretreatment and enzymatic hydrolysis of *Miscanthus x giganteus* to fermentable sugars. *Biotechnol. Prog.* 23(4), 846–850.

NASS. 2005. National Agricultural Statistics Service. *North Dakota Agricultural Statistics: Wheat Acres Harvested and Yields*. Quick Stats 2.0 Internet Website: http://nass.usda.gov/quickstats/. Washington, D.C.: US Department of Agriculture.

NASS. 2013b. National Agricultural Statistics Service. *Quick Stats 2.0* Internet Website: http://quickstats.nass.usda.gov/. Washington, D.C.: US Department of Agriculture.

NASS 2006. National Agricultural Statistics Service. *North Dakota Agriculture*. Ag Statistics No. 75. Fargo: North Dakota State University, ND Department of Agriculture and US Department of Agriculture, cooperatively.

NASS. 2007. National Agricultural Statistics Service. *North Dakota Agriculture*. Ag Statistics No. 76. Fargo: North Dakota State University, ND Department of Agriculture and US Department of Agriculture, cooperatively.

NASS. 2008. National Agricultural Statistics Service. *North Dakota Agriculture*. Ag Statistics No. 77. Fargo: North Dakota State University, ND Department of Agriculture and US Department of Agriculture, cooperatively.

NASS. 2009. National Agricultural Statistics Service. *North Dakota Agriculture*. Ag Statistics No. 78. Fargo: North Dakota State University, ND Department of Agriculture and US Department of Agriculture, cooperatively.National Agricultural Statistics Service. 2010. *North Dakota Agriculture*. Ag Statistics No. 79. Fargo: North Dakota State University, ND Department of Agriculture and US Department of Agriculture, cooperatively.

NASS. 2011. National Agricultural Statistics Service. *North Dakota Agriculture*. Ag Statistics No. 80. Fargo: North Dakota State University, ND Department of Agriculture and US Department of Agriculture, cooperatively.

NASS. 2012. National Agricultural Statistics Service. *North Dakota Agriculture*. Ag Statistics No. 81. Fargo: North Dakota State University, ND Department of Agriculture and US Department of Agriculture, cooperatively.

NASS. 2013a. National Agricultural Statistics Service. *North Dakota Agriculture*. Ag Statistics No. 82. Fargo: North Dakota State University, ND Department of Agriculture and US Department of Agriculture, cooperatively.

NASS. 2008. National Agricultural Statistics Service. North Dakota 2008 Feedlot Survey, North Dakota Field Office, Fargo, ND http://www.nass.usda.gov/Statistics_by_State/North_Dakota/Publications/Livestock,_Poultry_and_Dairy/feedlot.pdf

NASS. 2014. National Agricultural Statistica Service. January 1, 2014 Cattle Inventory. Washington, D.C., US Department of Agriculture, http://usda01.library.cornell.edu/usda/current/Catt/Catt-01-31-2014.pdf, viewed March 18, 2014.

Office of Management and Budget. 1972. *Standard Industrial Classification Manual.* Prepared by the Statistical Policy Division, Executive Office of the President. Washington, D.C.: U.S. Government Printing Office.

Ottman, Michael J., Thomas A. Dorge, and Edward C. Martin. 2000. *Durum Grain Quality as Affected by Nitrogen Fertilization Near Anthesis and Irrigation During Grain Fill*. Agronomy Journal 92: 1035 - 1041.

Palmqvist, B. and Liden, G., 2012. Torque measurements reveal large process differences between materials during high solid enzymatic hydrolysis of pretreated lignocellulose. Biotechnol. Biofuels 5, 57.

Pennington, Dennis. 2013. Harvest Index: *A Predictor of Corn Stover Yield*. Internet Website: http://msue.anr.msu.edu/news/harvest_index_a_predictor_of_corn_yield. East Lansing: Michigan State University, Extension Service.

Perry, Steve. 2013. *Fall 2013 Fertilizer Price Quotes*. Personal Communication. Buffalo, ND: the Arthur Companies Station Manager.

Petrolin, Daniel R. 2009. *Economics of Crop Residues: Corn Stover*. Internet Website: http://www.farmfoundation.org/news/articlefiles/17. Mississippi State: Mississippi State University, Department of Agricultural Economics.

Ransom, Joel K. 2004. Personal Communications. Fargo: North Dakota State University, Department of Plant Sciences, Extension Specialist, Cereal Crops.

Petry, Tim. 2014. Person Conversation. Fargo: North Dakota State University Cooperative Extension Service, Livestock Specialist.

Rijal, B., Igathinathane, C., Karki, B., Yu, M., Pryor, S.W., 2012. Combined effect of pelleting and pretreatment on enzymatic hydrolysis of switchgrass. Bioresour. Technol. 116, 36-41.

Roche CM, Dibble CJ, Knutsen JS, Stickel JJ, Liberatore MW. 2009. Particle concentration and yield stress of biomass slurries during enzymatic hydrolysis at high-solids loadings. Biotechnol Bioeng 104:290–300.

Sendich E, Laser M, Kim S *et al.* 2008. Recent process improvements for the ammonia fiber expansion (AFEX) process and resulting reductions in minimum ethanol selling price. *Bioresour. Technol*. 99(17), 8429–8435.

Sluiter, J.B., Ruiz, R.O., Scarlata, C.J., Sluiter, A.D., Templeton, D.W., 2010. Compositional analysis of lignocellulosic feedstocks. 1. Review and description of methods. J. Agric. Food Chem. 58, 9043-9053.

Tillner-Roth R, Friend DG. 1998. A Helmholtz free energy formulation of the thermodynamic properties of the mixture {water + ammonia}*. J. Phys. Chem. Ref. Data* 27(1), 63–96.

Sokhansanj, S. and Hess, J.R., 2009. Biomass supply logistics and infrastructure. Methods Mol. Biol. 581, 1-25.

Temmerman M, Rabier F, Jensen PD, Hartmann H, Bohm T. 2006. Comparative study of durability test methods for pellets and briquettes. *Biomass Bioenergy* 30(11), 964–972.

Teymouri F, Laureano-Perez L, Alizadeh H, Dale BE. 2005. Optimization of the ammonia fiber explosion (AFEX) treatment parameters for enzymatic hydrolysis of corn stover. *Bioresour. Technol*. 96(18), 2014–2018.

Theerarattananoon, K., Xu, F., Wilson, J., Staggenborg, S., Mckinney, L., Vadlani, P., et al., 2012. Effects of the pelleting conditions on chemical composition and sugar yield of corn stover, big bluestem, wheat straw, and sorghum stalk pellets. Bioprocess Biosyst. Eng. 35, 615-623.

Thompson, D.N., Campbell, T.J., Bals, B., Runge, T., Teymouri, F., 2013. Chemical preconversion: application of low-severity pretreatment chemistries for commoditization of lignocellulosic feedstock. Biofuels 4(3), 323-340.

Van Soest, P.J. 1973. Collaborative study on acid-detergent fiber and lignin. J. AOAC Int. 56:781-784.

Viamajala, S., McMillan, J.D., Schell, D.J., Elander, R.T., 2009. Rheology of corn stover slurries at high solids concentrations – Effects of saccharification and particle size. Bioresour. Technol. 100, 925-934.

Weimer, P.J., B.S. Dien, T.L. Springer, and K.P. Vogel. 2005. In vitro gas production as a surrogate measure of the fermentability of cellulosic biomass to ethanol. Appl. Microbial Biotechnol 67:52-58.

Zhou B, Ileleji KE, Ejeta G. 2008. Physical property relationships of bulk corn stover particles. *ASABE Trans*. 51(2), 581–590.

Zhu, Y., Malten, M., Torry-Smith, M., McMillan, J.D., Stickel, J.J., 2011. Calculating sugar yields in high solids hydrolysis of biomass. Bioresour. Technol. 102, 2897-2903.