2008

Nutrient recycling in biofuel production systems: biomass ash pelleting, ethanol co-product allocation, and a beef-ethanol production system analysis

Katherine A. Edwards
Iowa State University

Recommended Citation

Edwards, Katherine A., "Nutrient recycling in biofuel production systems: biomass ash pelleting, ethanol co-product allocation, and a beef-ethanol production system analysis" (2008). *Retrospective Theses and Dissertations*. 15329.
http://lib.dr.iastate.edu/rtd/15329

Nutrient recycling in biofuel production systems: biomass ash pelleting, ethanol co-product allocation, and a beef-ethanol production system analysis

by

Katherine A. Edwards

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Co-majors: Agricultural Engineering; Biorenewable Resources and Technology

Program of Study Committee:
Robert P. Anex, Major Professor
D. Raj Raman
Matthew Z. Liebman

Iowa State University

Ames, Iowa

2008

UMI Number: 1453145

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

The earth is the Lord’s and the fullness thereof…
All that I have created is good… now go and do likewise.
- God

Taken from Psalms 24, Genesis 1, Ephesians 2:10

To my parents, for teaching me that God cares immensely about all his creation.
To my grandparents, who helped me see beauty in creation;
Instilling in me a love of the land.
To Dr. Anex for teaching me to discover, investigate and communicate effectively,
And to each person who helped launch and encourage me on this journey of learning.

TABLE OF CONTENTS

Acknowledgements

I would like to acknowledge Dr. Robert Anex, my major professor for mentoring me as an undergraduate student and encouraging me to pursue graduate school; he had confidence in my potential and undertook the hard work to bring it out. I am grateful to him for enabling, encouraging and teaching me in the process. I would also like to acknowledge my committee members Dr. Matt Liebman and Dr. Raj Raman for their generosity to me with their time, patience and knowledge, Dr. Mary Wiedenhoeft for her kindness, encouragement and advice about my research, and Asli Isci and my other office mates for fun frisbee games and serious research discussions which aided me in the process. I would like to thank the many people who contributed to each project whose names are included at the end of each chapter. I would like to acknowledge my parents for giving me an educational foundation and instilling in me a love of learning, and my sisters Elizabeth, and Laura and her family, my grandparents, aunts, uncles and cousins who encouraged me and helped me play in the process and to Alan and Laurie Jensen for loving me and cooking me many meals that helped me finish this thesis and Dr. Kim Conger and Lori Adams for their encouragement. Finally, to my family and to the Jensen's, Kim, Lori and Mary thank you for living out the worldview and mindset of the integration of spirituality in all of life.

Abstract

Biofuels are potentially carbon-neutral fuels because the carbon emitted during combustion of the fuel was recently absorbed from the atmosphere by the biomass feedstock as it grew. Relative to fossil fuels, biofuels help to close the carbon cycle; however other essential nutrient cycles remain open. When biomass is removed from the agricultural landscape essential plant nutrients such as nitrogen (N), phosphorus (P), and potassium (K) are also removed. These nutrients are not present in refined biofuel products. Instead they are concentrated in biorefinery waste streams and low value co-products.

The economic and environmental sustainability of biofuel production systems can be enhanced by capturing these nutrients and returning them to the crop fields, thereby reducing the energetic and economic costs of fertilization. This thesis comprises three analyses related to nutrient cycles in the emerging bioeconomy. In the first, ash generated during the production of ethanol was pelleted and then evaluated as a potential fertilizer. It was found that binder type and level have a significant effect on the physical and chemical characteristics of the pellets, and that the degradability and durability of the pellets are inversely related. Preliminary data suggest ash pellets cost 86% less to produce than the cost of purchasing the potash and phosphate fertilizer the pellets would replace when used as a fertilizer.

As a fertilizer, biorefinery ash becomes a valuable co-product of the biorefinery rather than a waste. Analysis of the environmental and energetic performance of biorefinery systems requires that the use of resources, such as energy used in processing, be allocated between the different products. In the second study in this thesis an energy co-product credit for corn dry grind ethanol production has been determined by examining the effect of variable inclusion rates of distillers grains (DG) in cattle diets. The co-product credit for dry grind ethanol production was estimated to range from 2.2 MJ/L to 4.3MJ/L depending on the type of DG added to the animal diet, the type of feed component displaced and the DG inclusion rate in the diet. This range of possible co-product credits dramatically impacts estimates of system net energy. Corresponding net energy calculations for a typical dry grind ethanol system ranges from 2.7 MJ/L to 4.8 MJ/L. This can be compared to a current dry grind ethanol net energy estimate of 4.6 MJ/L.

In the third analysis, the net energy and spatial concentration of nutrients and water consumption have been determined for an integrated beef-ethanol production system that benefits from recovering energy from co-product streams and co-locating complementary unit processes. The system combines a 95 x 10^6 L/yr (25 x 10^6gallons/yr) ethanol plant and a 17,000 head cattle concentrated animal feeding operation. The net energy of the integrated system was estimated to be 13.7 MJ/L compared to 4.6 MJ/L for a non-integrated corn dry grind ethanol plant. The integrated system requires twenty-eight thousand hectares for spreading the reclaimed nutrients from the manure and thin stillage and consumes 7.1 L_{water}/L_{EtOH}, compared to 3.45 L/L_{EtOH} in a conventional system.

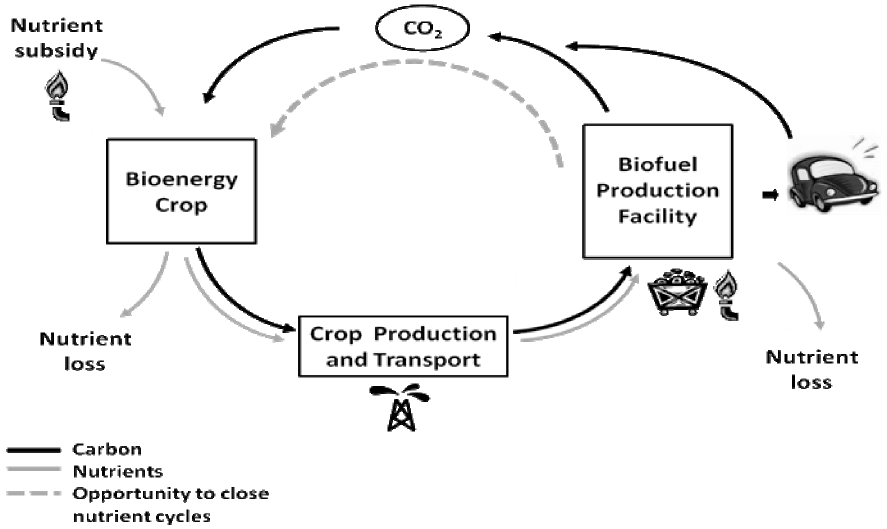
CHAPTER 1

General Introduction

The recent surge in biofuel production stems from a desire to (1) increase US energy independence from foreign oil, (2) develop value added agricultural products, and (3) promote rural economic development (Lynd et al. 1991; Greene et al. 2004; Spatari et al. 2005; Farrell et al. 2006). When biomass is taken off the land to be turned into biofuels, other nutrients are also removed that are not needed for the production of the hydrocarbon fuel. Farmers in the United States use 19.4 x 10^9 kg of fertilizer every year to produce agricultural crops (USDA, 2007). With increased removal of crop residues such as corn stover for use as biofuel feedstock fertilizer use is expected to increase (Laird, 2008). For example, Hoskinson et al. (2007) estimate that \$57.36 ha^{-1} of macronutrients are removed when harvesting corn stover using a normal cutting scenario, which leaves 24% of the residue on the soil. As well as increasing the need for synthetic fertilizer application, removing residues may further short-circuit nutrient cycles in the agro-ecosystem creating water quality concerns in river and estuarine systems (Rabalais, 2002).

During biofuel production, nutrients contained in biomass feedstocks are concentrated in low value waste streams and byproducts at biofuel production facilities. Biofuel production aids in closing the carbon cycle. When recently fixed carbon in plant material is made into fuel and emitted during production and utilization of the fuel, it is returned to the atmosphere or incorporated in the soil as agricultural residue, manure or other waste products. Although carbon cycles are partially closed, other nutrient cycles remain open (Figure 1). The black line in figure 1 represents the carbon cycle in biofuel production. Carbon in plant material is transformed into bio-fuels and CO_2 emitted from the production and utilization of the fuel is sequestered back into the soil by bioenergy crops. The gray line in figure 1 represents the pathways of essential plant nutrients such as nitrogen, phosphorus and potassium in biofuel production. Nutrients contained in the biomass are not necessarily returned to the soil and often leach from the system from erosion and in waste products at the production facility. The dotted gray line denotes the opportunity to return these nutrients back to the field as fertilizers and soil amendments. Recovering nutrients from biofuel production potentially reduces the energy and cost of fertilization and reduces the amount of nutrients added to the agricultural ecosystem, improving the health of rivers and streams degraded from nutrient rich agricultural run off.

Figure 1: Carbon and other nutrient cycles in biofuel production



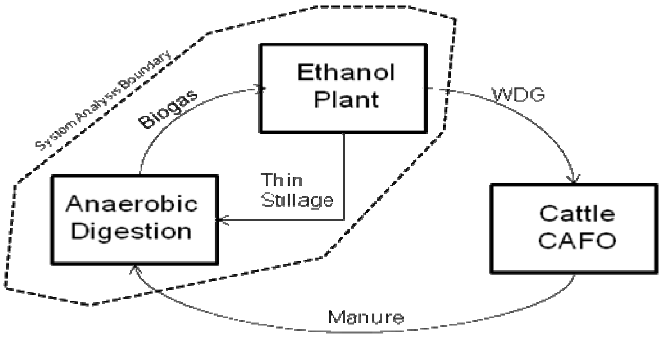
A growing number of ethanol facilities are adding solid fuel boilers burning biomass to produce process heat, in place of increasingly expensive natural gas and coal, further reducing the external carbon inputs to the system. Combustion of biomass to provide process heat concentrates nutrients in an ash stream. In integrated cellulosic biofuel production it is anticipated that biochemical processes will convert biomass to fuels and fermentation residue will be thermochemically converted to fuels and energy. Thermochemical conversion, such as gasification concentrates nutrients (e.g., potassium and phosphorus) into a ash stream and gas stream (e.g., nitrogen). Recovering these nutrients as fertilizer provides an opportunity to recycle nutrients back to the soil improving the energetic and economic efficiency of the biofuel system (Anex et al., 2007).

Closing nutrient cycles in biofuel production through recycling pyrolysis char has the potential to increase soil carbon while closing other nutrients cycles, but char application is difficult due to its powdery and reactive properties (Laird, 2008; Lehmann, 2007). Biomass ash, like char, is a nutrient rich byproduct from thermochemical conversion and contains essential plant nutrients that can be used as fertilizer. Like char, ash is lightweight and difficult to apply. Pelleting biomass ash is one way to make it easier to transport and apply. In this study ash was pelleted using three binders, three moisture contents and three binder levels. The physical and chemical properties of the pellets were tested using a face-centered response surface experimental design. Data were analyzed using a three-way factorial analysis of variance. The effects of binder type, binder level and moisture content on the physical and chemical properties of the pellets have been evaluated.

The energy associated with the production of co-products, such as useful nutrient rich streams exiting the system, is needed to determine the net energy of biofuel production systems. In corn dry grind ethanol production, nutrients are concentrated in the co-products, distillers grains, which are predominately used for animal feed. Co-product allocation is a method of distributing and assigning production energy between multiple product streams (Wang, 1999; Kim and Dale, 2002; Shapouri et al. 2002; Graboski, 2002). In allocation for corn ethanol production, the total production energy is allocated between ethanol and distillers grain by determining the life cycle energy required to produce the feed that is displaced by the distillers grains. Typically it is assumed that a set proportion of distillers grains is fed in cattle diets, however, in practice cattle are fed varying amounts of distillers grains. In this study co-product credits have been calculated for actual animal feed rations varying the amount of distillers grains included in the diets.

One system that benefits from nutrient recovery and utilizes co-product credit allocation is an integrated beef cattle concentrated animal feeding operation and ethanol plant. In one integrated design, wet distillers grain is fed to cattle, while cattle manure and thin stillage – the liquid portion of distillers grains separated after centrifugation of the distillation bottoms – is fed to an anaerobic digester which provides the process heat for the facility (Figure 2). Integrating beef and ethanol production increases the ethanol system net energy compared to a stand-alone dry grind ethanol process, because of the biogas produced and the lack of drying distillers grains, but the integrated system spatially concentrates nutrients and water consumption. Nutrients are concentrated in the anaerobic digestion sludge. In this thesis, the system net energy, water consumption and the land area needed for application of nutrients concentrated in the anaerobic digester, were estimated for a representative integrated beef-ethanol system. The system boundary was drawn around the ethanol plant and anaerobic digester so the net energy would be easily comparable to a stand alone dry grind ethanol plant (Figure 2).

Figure 2: Integreted beef-ethanol system



Recycling nutrients in biofuel production has the potential to enhance both the economic and environmental sustainability of production systems. Pelleting biomass ash is one method of recycling nutrients in biofuel production. Co-product credit allocation provides a means for estimating the energetic and environmental costs of these streams. Integration of a beef-ethanol production system utilizes ethanol co-product credit allocation and has the potential to recycle nutrients back to the agricultural landscape.

References

Anex, R.P., Lynd, L. R. Laser, M.S., Heggenstaller, A.H. , Liebman, M., 2007. Potential for enhanced nutrient cycling through coupling of agricultural and bioenergy systems. Crop Sci. 47, 1327–1335.

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M., Kammen, D.M., 2006. Ethanol can contribute to energy and environmental goals. Science 311, 506-508.

Graboski, M.S., 2002. Fossil energy use in the manufacture of corn ethanol. Prepared for the National Corn Growers Association.

Greene, N., Celik, F.E., Dale, B., Jackson, M., Jayawardhana, K., Jin, H., Larson, E.D., Laser, M., Lynd, L., MacKenzie, D., Mark, J., McBride, J., McLaughlin, S., Saccardi, D., 2004. Growing energy: How biofuels can help end America's oil dependence. Natural Resources Defense Council, New York, NY. On-line: http://www.nrdc.org/air/energy/biofuels/biofuels.pdf.

Hoskinson, R., Karlen, D.L., Birrell, S.J., Radtke, C.W., Wilhelm, W.W. 2006. Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. Biomass and Bioenergy. 31, 126-136.

Kim, S., Dale, B.E. 2002. Allocation procedure in ethanol production system from corn grain. I. System expansion. Int. J. LCA. 7, 237-243.

Laird, D.A. 2008. The Charcoal Vision: A win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. Agronomy Journal. 100, 178-181.

Lehmann, J. 2007. A handful of carbon. Nature. 447, 143-144.

Lynd, L. R., Cushman, J.H., Nichols, R.J., Wyman, C.F., 1991. Fuel ethanol from cellulosic biomass. Science 231: 1318-1323.

Rabalais, N. N. 2002. Nitrogen in aquatic ecosystems. AMBIO 31(2):102–112.

Shapouri, H., Duffield, D.A., Wang, M., 2002. The energy balance of corn ethanol: An update. USDA Agricultural Economic Report Number 814.

Spatari, S., Zhang, Y., MacLean, H., 2005. Lifecycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. Environmental Science and Technology 39: 9750-9758.

USDA Economic Research Service. 2007. U.S. Fertilizer Use and Price. Table 1—U.S. consumption of nitrogen, phosphate, and potash for 1960-2006. Available online at: http://www.ers.usda.gov/Data/FertilizerUse/. Accessed 30 March, 2008.

Wang. M.. 1999. GREET 1.5 – Transportation Fuel Cycle Model, Volume 1: Methodology, Development, Use and Results. Argonne National Laboratory, Illinois, USA.

CHAPTER 2

Recycling Nutrients from Biofuel Production: Pelleting and Characterizing Biomass Ash

Edwards, K. A.(1), Anex, R. P.(1)*

A paper to be submitted to *The Journal of Bioresource Technology*

Abstract

The economic and environmental sustainability of biofuel production can be enhanced through returning essential plant nutrients unutilized in biofuel production back to farm fields. Plant nutrients contained in biomass feedstocks usually exit biofuel conversion processes as unwanted waste or low value co-products. Essential plant nutrients appear, for example, in dried distillers grains with solubles (DDGS), and condensed distillers solubles (CDS) in the dry-grind ethanol process. With integrated biorefineries designed to produce cellulosic ethanol, plant nutrients will exit the facility in the gas and ash streams generated by the thermochemical conversion processes that utilize biomass residue produced from fermentation. Ash produced from combustion of biomass has a high pH, is often rich in phosphorus, potassium and calcium and could be applied as a soil amendment (i.e., fertilizer and liming agent). However, combustion ash is a low-density powder and is therefore difficult to handle and store. Field application is particularly difficult due to dispersion and health concerns. Pelleting ash is one solution for making ash more practical as a fertilizer. In this study, CDS combustion ash was pelleted using three different bioprocess by-product as binders, DDGS, CDS and bone meal--a low grade by-product of animal rendering. Physical and chemical characteristics of the pellets were evaluated using standard methods. We successfully pelleted biomass ash and found that DDGS and bonemeal pellets had the highest durability and degradability. CDS was found to not be a suitable binder, due to pellets resulting in extremely low durability. We also discovered that there is a trade-off between the durability and degradability of ash pellets. While ash contains significant levels of essential nutrients, greenhouse studies and field trials will be necessary to determine the bioavailability of pellet-bound nutrients. Assuming total nutrient availability, preliminary data suggest ash pellets cost 86% less to produce than purchasing the potash and phosphate commercial fertilizer the ash would replace. Pelleting biomass ash can create an opportunity for recycling nutrients in biofuel production, enhancing both the environmental and economic sustainability of the system.

* corresponding author (rpanex@iastate.edu)

(1) Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50010

Introduction

Biofuel production helps to close the carbon cycle by taking advantage of plants' ability to fix carbon. When carbon embedded in plant material is made into fuel and emitted during production and utilization of the fuel it either returns to the atmosphere or is incorporated in the soil as agricultural residue, manure, or other waste products. Although the carbon cycle is being closed, other nutrient cycles remain open. Essential plant nutrients such as nitrogen (N), potassium (K) and phosphorus (P) are not used in biofuel production and usually exit the system in waste streams or low value by-products. The economic and environmental sustainability of biofuel production can be enhanced by capturing these nutrient rich by-products and returning them to the soil as fertilizer.

Integrated lignocellulosic biofuel production facilities envisioned for the future will concentrate nutrients in by-products from thermochemcial conversion. Thermochemical conversion will produce the heat and power to drive the biochemical conversion of biomass, while residue from the biochemical process will fuel the thermochemical process. Currently, nutrients that enter thermochemical conversion as part of the lignocellulosic biomass concentrate in fly ash (e.g., phosphorus, potassium) or in the case of nitrogen, are released as ammonia gas (Anex et al. 2007).

An increasing number of ethanol plants are adding solid fuel boilers or gasification systems on the front end of their plant to supplement natural gas or coal use (Kotroba, 2006; Morey, 2007; CVEC, 2006). Corn Plus Ethanol, in Winnebago, Minnesota, a 190 x 10^6 L/yr (50 million gal/year) corn dry grind ethanol plant, is generating over 8100 tonnes of nutrient rich ash per year from combusted biomass (Nilles, 2007). Currently, facilities have to pay tipping fees to dispose the ash at landfills. But this ash could be a valuable soil amendment if it were recycled back to the soil. The purpose and goal of this study is to pellet biomass ash for its potential use as a fertilizer.

Biomass ash typically contains significant amounts of potassium and phosphorus (Stehouwer et al. 1999). It is rich in carbon (Laird, 2008; Lehmann, 2007) and its use as a fertilizer has been advocated since the 1700's (Eliot, 1934). Alfalfa ash is known to be high in phosphorus and potassium (Mozzafari et al. 2000a, 2000b and 2002). Wood ash has significant amounts of potassium, phosphorus and calcium, offering the potential to be used as a P and K fertilizer (Etiegni et al. 1991a,b). Due to its high pH and calcium content ash could also be used as a liming agent. Using ash as a soil amendment will return concentrated nutrients back to the soil and reduce the need for synthetic fertilizer.

Transforming the physical nature of ash and characterizing its chemical and physical properties is necessary before it will become a useful commercial soil amendment or fertilizer. Ash is difficult to store, transport and apply due to its reactivity and light, powdery texture. Pelletizing, a type of systematic agglomeration, has the potential to solve the difficult application issues by densifying ash so that it can be transported, stored and applied effectively to crop ground, minimizing loss and air pollution concerns during application.

Agglomeration, the sticking together of small particles, is used in many applications including the production of pharmaceuticals, cereal and snack food, fertilizer and agro-chemicals, animal feed, solid fuels and minerals and ores (Pietsch, 2005). There are two main agglomeration technologies, tumble/growth (gravity assisted agglomeration), and extrusion (pressure assisted agglomeration) (Pietsch, 2005). Producing pellets through pressure agglomeration is called pelleting, producing pellets with gravity assisted agglomeration is called pelletization. Pelletizing generally refers to growth agglomeration but is often used as a synonym for agglomeration (Pietsch, 2002).

Extrusion technologies are commonly used for snack, cereal, chemicals, pet food, livestock feed, stove pellets and in plastic production. Pan pelletization, a type of tumble/growth agglomeration technology uses gravity, moisture and a binder and is commonly used for making limestone pellets and iron ore pellets (Pietsch, 2005). Feed pellet mill technology, a type of extrusion technology, commonly used to pellet animal feed and solid fuels, was used to pellet ash in this study.

Materials similar to ash, with high carbon content, consisting of small particulate matter have been transformed or agglomerated for many years. In the 1920's, charcoal briquetting became common (Begole, 1970), and in the 1930's carbon black, produced from incomplete combustion of coal was pelletized using agitation and compression (Price, 1938). More recently, coal fly ash used in concrete production (Bland et al. 1992) and rice hull ash used for insulation to prevent rapid cooling of molten steel (RHR; Agrielectric) have been pelletized with pan pelletization technology. Wood ash has been agglomerated using roll pelleting equipment and used for nutrient recovery in forest soils (Sarenbo and Claesson 2004).

In this study we pelleted and characterized ash from combusted biomass using three bioprocessing byproducts as binders, and determined the effect of moisture content, binder level and binder type on the pellets physical and chemical properties.

Materials and Methods

The ash used in this study was produced at Corn Plus Ethanol (Winnebago, MN), from co-firing condensed distillers solubles--a by-product from ethanol production--with natural gas in a fluidized bed combustion system to produce process heat for the plant (Nilles, 2007).

Animal feed pellet milling technology was used to agglomerate the ash. A binder was used to effectively pelletize the ash and avoid plugging the pellet mill dye. We chose to use bioprocessing by-products as binders because they lower the cost of using the ash as a potential fertilizer. Binders used for agglomeration in the pellet mill were bone meal--a low grade by-product from animal rendering, dried distillers grains with solubles (DDGS), and condensed distillers solubles (CDS). DDGS and CDS are by-products from corn grain ethanol production and are commonly blended with animal feed.

We analyzed our data for explanatory purposes with SAS statistics software (http://www.sas.com) using a three-way factorial analysis of variance. Effects of binder level, moisture content, binder type and evidence of interaction were measured for each of the response variables. A Tukey-Kramer multiple comparison test was used to determine statistical differences between responses from treatments with different binder types and levels.

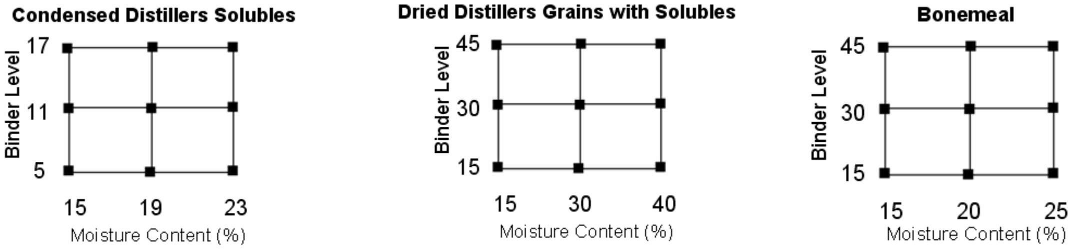
Low, medium, and high factor levels for each binder type were chosen. These levels were relative to acceptable operating ranges for each binder type. Equal variance was assumed within binder types. Lab tests were performed to determine acceptable operating ranges for binder level and moisture content by observing the texture of the individual mixtures and determining a workable consistency for the pellet mill. Each of the three binders when mixed with the ash created different consistencies, thus the binder levels and moisture contents chosen for each binder are different (Figure 1). Each black dot in figure 1 represents a separate treatment. Binder levels for bone meal and DDGS were similar since they both have a dry consistency. But they absorb different amounts of water so the moisture content for the mixtures differed. CDS has high moisture content (70%) so it was oven dried to 50% moisture before it was added to the ash; however, the level of binder we could add before the mixture became too wet was still much lower than for the other binders.

For predictive purposes three dimensional response surface designs were generated using the statistical analyses software, R Project (http://www.r-project.org/). Response surface methods (RSM) use experimental data to create multidimensional surfaces that predict the effect of multiple factors on multiple response variables (Khuri and Cornell, 1987). A separate response surface design is created for each response by using the data and a model to predict the responses within the factor ranges. In a two factor study, the factors create an x-y surface. The response is plotted on the z axis, creating a three dimensional model. Response surface designs (RSD) can be used for exploratory purposes and to optimize responses. These designs require fewer replicates than full factorial designs and are commonly used in the experimental design process for pilot scale experiments where time or cost is a constraint on treatment replication. In RSM designs, replication is strategically placed to avoid complete replication while still generating useful information (Khuri and Cornell, 1987).

In this experiment RSD were created for each response variable separated by binder type. A face-centered central composite design with triplicate center points was utilized using a second order polynomial to fit the response surface. A face centered design was chosen over a central composite design with stars because the region of operability was the same as the region of interest (Khuri and Cornell, 1987). The graphs in figure 1 represent the x-y axis of the response surfaces that were generated for each response variable.

Thirty-three 2 kg treatments were pelleted in random order. Independent explanatory variables were binder type, binder level (BL) and moisture content (MC). Dependent response variables were durability, degradability, liming capacity, total carbon, total nitrogen, total potassium, total phosphorus, water soluble inorganic nitrogen, water soluble potassium, and water soluble phosphorus.

Figure 1: Face centered response surface design treatment structure



Each treatment was pelleted in a California feed pellet mill (Model CL5). The samples were prepared by weighing specific levels of ash, binder, and water. Each treatment was homogenized before and after water was added to create the desired moisture content. Ash and binder percentages were determined on a dry matter basis. Mixtures were double bagged and stored at 4°C for a minimum of 12 hours to allow sample moisture content to equilibrate. Each treatment was fed into the pellet mill and augured into a die where the material was extruded. Cylindrical pellets were made as the dye rotated and material was extruded from the die and cut by a knife, resulting in pellets falling from the die. The dye was thoroughly cleaned after each treatment to avoid contamination by feeding soybean meal through the pellet mill to lesson the compaction in the dye than using compressed air to clean the dye holes. The pellets were air dried at 18°C, then physically and chemically characterized.

Previous studies chemically characterizing biomass ash usually report total (Mozaffari et al. 2000b; Sarenbo and Claesson, 2004) or available nutrients (Stehouwer et al. 1999; Huang et al. 1992) or both total and available nutrient levels (Patterson et al. 2004) in the ash. Steenari et al. (1998) characterized water soluble nutrients in wood ash by adding water to the ash then decanting and testing the nutrient levels in the water. Total nutrient levels in these studies were obtained using varying acid strengths. These affected the nutrient levels found. The available nutrient levels in these studies were determined using soil testing procedures. However soil tests yield varying results depending upon soil type and pH (Havlin et al. 1999). Because ash is added as an amendment to the soil, testing the ash alone does not identify what nutrients are available to the plant. Nutrient bioavailability of the ash depends upon the type and pH of the soil to which the ash is added as well as environmental conditions.

Though the bioavailability was our primary interest, in this study we determined the water soluble and total nutrient content of our ash pellets. This provides a range of available nutrients contained in our ash pellets. Total nitrogen and carbon were determined using a LECO TruSpec CHN analyzer (St. Josephs, MI).Total potassium and phosphorus were determined with nitric acid digestion followed by inductively coupled plasma spectroscopy (ICP) (EPA 3050B, 1996). Water soluble nutrient content was determined by dissolving ground pellet samples in water using the method described in Huang and Schoenau (1998). The water soluble solution was analyzed for P and K content with ICP. Water soluble inorganic nitrogen was analyzed using a Lachat auto analyzer system. The liming equivalency or effective calcium carbonate equivalence (ECCE) of the pellets was tested using agricultural liming material methods (AOAC, 2007). The chemical tests and liming capacity were performed by the Iowa State University Soil Testing Lab (Ames, IA).

The pellet durability (ASAE, 1996) and degradability (AOAC, 2007), both important physical properties, were tested. The pellets need to be durable enough to transport to the field but also posses characteristics that allow degradation soon after soil application, making the contained nutrients available to the plants. Pellet durability is a common and useful test for predicting feed pellet handling and transport suitability. The durability was determined by obtaining a 500gram pellet sample by sieving the pellets through a 3.35 mm screen then tumbling the sample for 10 minutes, then measuring the fines that pass through the 3.35 mm screen. The resulting durability is the percent of pellets that did not degrade during tumbling (ASAE, 1996). Water degradability, useful for predicting the degradation rate of the pellets in the field, is a portion of the ECCE test and measures the percentage of material that passes through a four, eight and fifty mesh screen when run under a steady stream of water.

Results and Discussion

Table 1 shows the F values and significance of each model effect for each response variable. The probability values produced from the three way factorial ANOVA model show that binder level and binder type significantly impact the model (Table 1). An interaction was present between binder type and binder level between all of the response variables except pH and water soluble K.

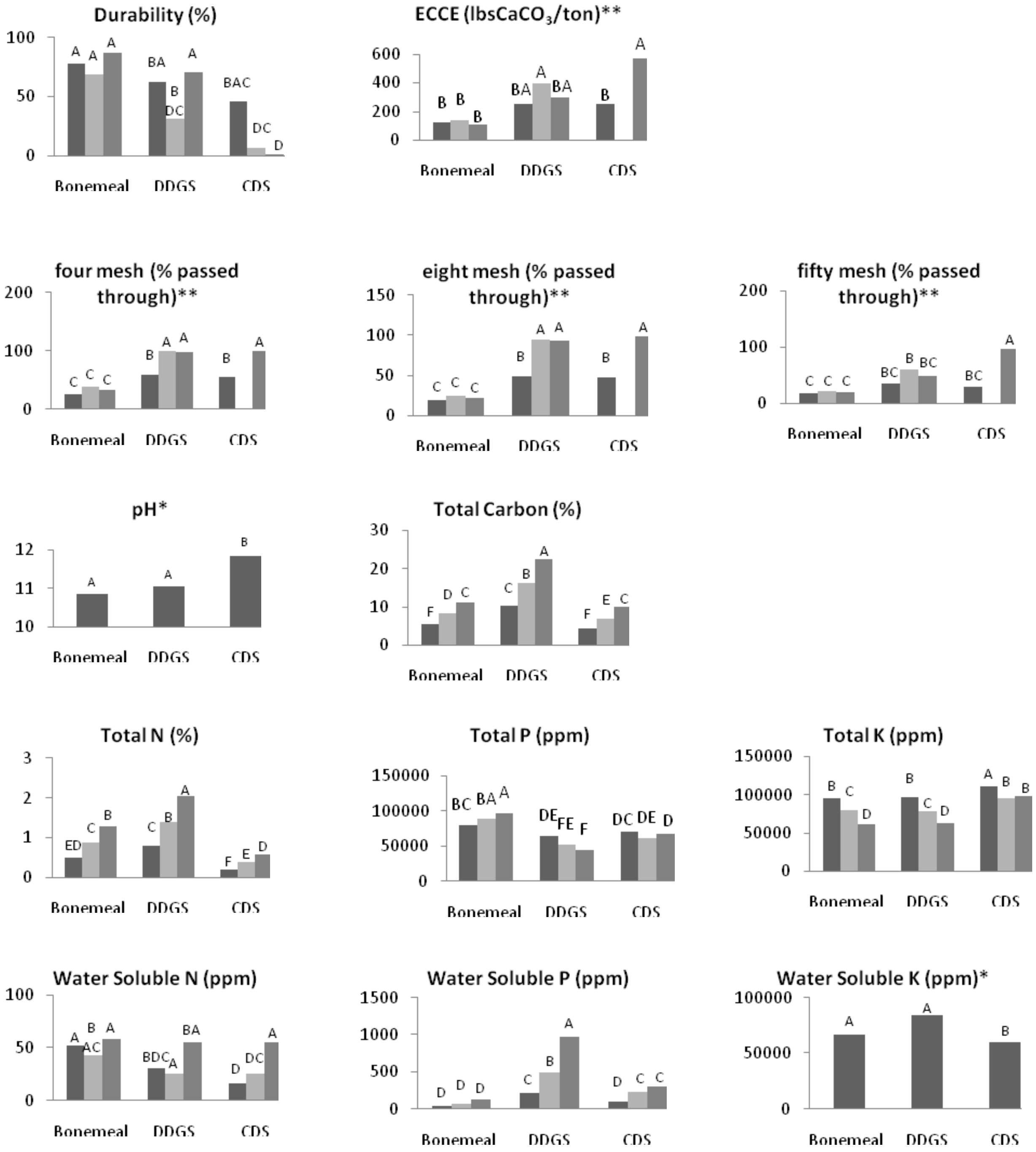
Because there is an interaction between binder type and binder level the mean binder responses are not meaningful. Figure 2 shows the mean binder responses separated by binder level for each response variable. From left to right on the graph, the three bars for each binder type show the responses for low, medium and high levels of binder. The letters on the bar graphs denote which treatments are statistically different.

Table 1: F statistics for the three way factorial ANOVA

Source	**MC**	**BL**	**MC*BL**	**Binder**	**MC*Binder**	**Binder*BL**	**MC*Binder*BL**
Durability (%)	7.44*	14.32**	2.51^{ns}	67.75***	2.39^{ns}	6.64*	2.11^{ns}
ECCE (lbs $CaCO_3$/ton pellets)	7.20*	18.18**	2.81^{ns}	78.40***	2.01^{ns}	8.74*	2.03^{ns}
pH	4.26^{ns}	3.49^{ns}	0.61^{ns}	11.23**	0.71^{ns}	3.17^{ns}	0.70^{ns}
Total Carbon (%)	0.26^{ns}	1044.60***	2.49^{ns}	1858.16***	0.63^{ns}	84.23***	3.47^{ns}
Total N (%)	0.42^{ns}	901.73***	1.33^{ns}	1598.33***	0.10^{ns}	90.54***	2.19^{ns}
Total P (ppm)	2.31^{ns}	3.37^{ns}	1.63^{ns}	250.74***	0.41^{ns}	22.03***	1.12^{ns}
Total K (ppm)	4.08^{ns}	649.24***	8.58*	624.70***	4.39^{ns}	54.96***	6.91*
Water Soluble N (ppm)	4.31^{ns}	27.79***	7.61*	25.99**	3.93^{ns}	13.61**	3.01^{ns}
Water Soluble P (ppm)	6.47*	472.47***	0.30^{ns}	1044.64***	2.19^{ns}	176.38***	2.51^{ns}
Water Soluble K (ppm)	2.62^{ns}	26.56**	0.37^{ns}	15.84**	1.30^{ns}	0.50^{ns}	0.80^{ns}
Fiftymesh (% passed through)	3.38^{ns}	21.88**	2.68^{ns}	54.10***	1.51^{ns}	10.64**	1.28^{ns}
Eightmesh (% passed through)	91.29***	362.91***	37.83***	1118.04***	30.46***	79.77***	36.11***
Fourmesh (% passed through)	53.83***	144.88***	29.85***	411.40***	13.91**	19.49**	23.12***

*p<0.05, **P<0.01, ***p<0.001, ns: P values not significant

Figure 2: Three-way factorial ANOVA mean binder-type/binder-level responses



*no interaction was present between BL and binder type so the effect of BL within binder type is not shown

** the ave. for CDS med. is not shown due to insufficiant material to test sample (CDS-med MC-med BL) pellets crumbled before testing

Bone meal in general had the highest durability, but was not statistically different than DDGS with low and high levels of binder and CDS with low levels of binder.

There is little information in the literature regarding standards for the durability of pellets in general; however, there is some information on the durability of feed pellets. Although there are other implications for the durability of feed pellets such as palatability, the goal both in feed pelleting and ash pelleting is to deliver material that stays in a pellet form, thus using feed pellet standards are useful comparison for ash pellets. Feed pellets with durability above 80% are considered adequate (Rosentrater, 2007). Swine have been fed pellets with durability as low as 62% (Hanrahan, 1984) and poultry fed pellets as low as 50% durability (Kenny, 2005). CDS at levels of med and high have extremely low durability. Because the durability of the CDS pellets is well below common durability values for feed pellets, CDS is not a suitable binder.

The liming equivalence of the pellets (ECCE) is a function of the water degradability of the pellets (4mesh, 8mesh and 50mesh). In general, CDS and DDGS had the most degradable pellets (highest ECCE value), however, low CDS and low and high DDGS were not statistically different than bone meal (Figure 2). DDGS and CDS also had the highest levels of four, eight and fifty mesh (Figure 2). The fifty mesh followed a similar trend as the ECCE results and bone meal was the lowest but not statistically different than DDGS low and high and CDS low (Figure 2).

CDS had the highest pH and was statistically different than bone meal and DDGS. DDGS had the highest total C and total N levels. Bone meal contained the highest total P levels. CDS had the highest total K overall, bone meal and DDGS were not statistically different than one another. Bone meal had the highest water soluble inorganic N but was not statistically different than DDGS medium and high and CDS high. DDGS med and high levels of binder had the highest water soluble P. Bone meal and DDGS had the highest water soluble K and were not statistically different than one another.

There is a trade-off between the degradability and the durability of pellets. In general bone meal created pellets with the highest durability but the lowest degradability. CDS and DDGS created pellets with the highest degradability in general but low durability, particularly in the case of CDS.

Thirty–nine RSD were generated to describe the effect of binder level and moisture content on each of the response variables for each binder type. Assuming equal variance within binder type, the variability described by the second order RSD adequately described the variability in our data for 32 of the models. Only 7 of the predictive models do not fit the data (Table 2).

Table 2: Fit of 2nd order response surface predictive model, *values are not significant (p>0.1)

Test	**Bone meal**		**CDS**		**DDGS**	
	p-value	**R^2**	**p-value**	**R^2**	**p-value**	**R^2**
Durability	0.008934	0.920	0.08102	0.796	0.08431	0.792
Fourmesh	0.1341*	0.743	0.09143	0.843	0.06647	0.813
Eightmesh	0.05122	0.833	0.0362	0.904	0.04689	0.839
Fiftymesh	0.08694	0.789	0.02390	0.923	0.3972*	0.561
pH	0.003469	0.946	0.07097	0.807	0.3398*	0.596
Total Carbon	0.0001066	0.987	4.361e-06	0.996	0.0003411	0.979
Total N	3.426e-06	0.997	1.103e-06	0.998	0.0002177	0.982
Total P	0.002572	0.952	0.5357*	0.479	0.02021	0.888
Total K	1.278e-05	0.994	0.1139*	0.762	0.001957	0.957

Table 2 continued

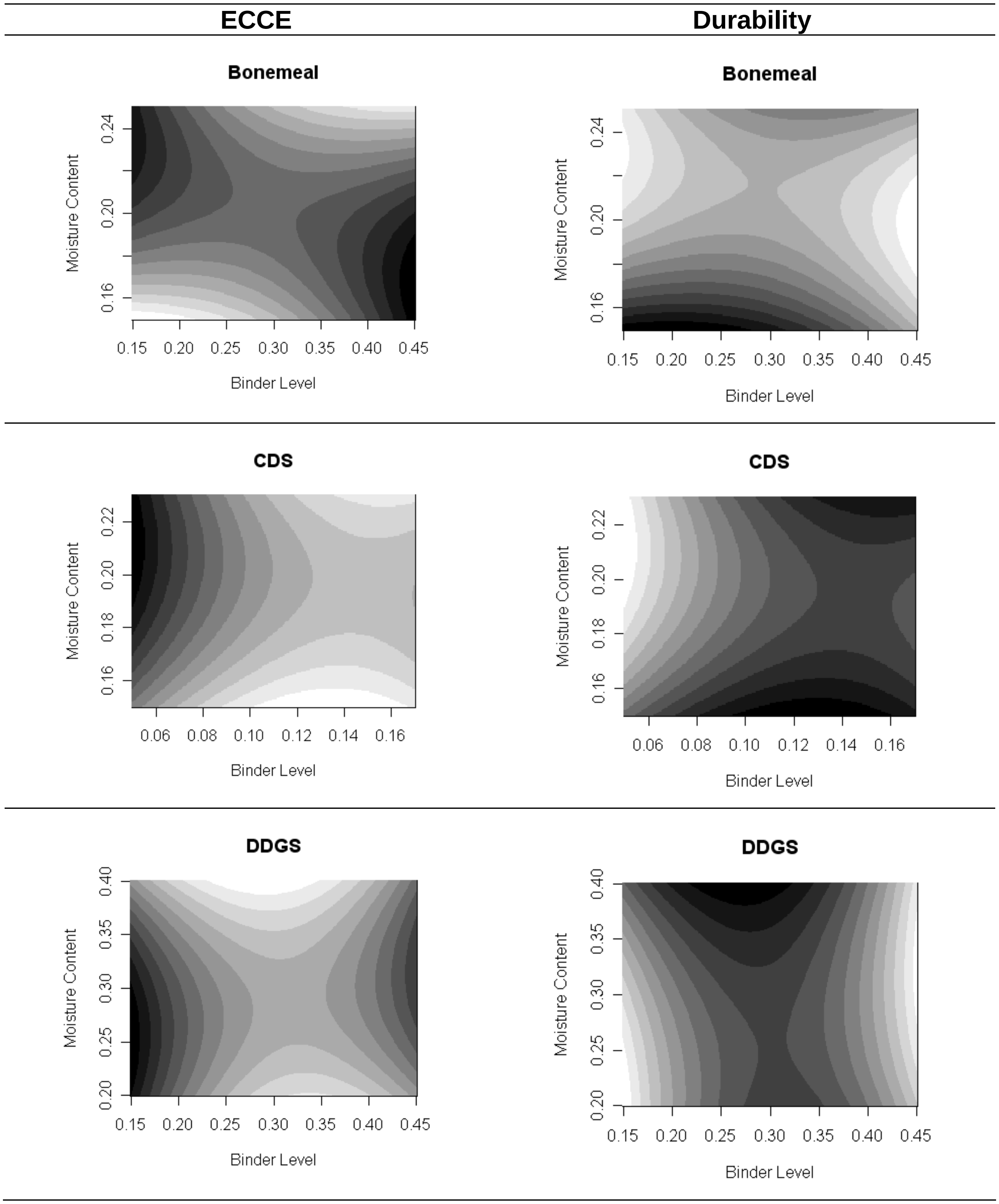
Test	**Bone meal**	**CDS**	**DDGS**			
	p-value	**R^2**	**p-value**	**R^2**	**p-value**	**R^2**
Water Soluble P	0.01443	0.904	0.002939	0.947	4.343e-05	0.991
Water Soluble K	0.006109	0.932	0.1019	0.774	0.03923	0.851

In table 1 the effect of binder level and binder type was illustrated however, moisture content was also significant for some of the response variables. Response surfaces display data for moisture content and binder level allowing for simultaneous analysis of each. Moisture content had an effect on Durability, ECCE, Water soluble P, eightmesh and fiftymesh. ECCE depends on eightmesh and fiftymesh and the RSD for ECCE summarizes the effect of both. The water soluble phosphorus (0.0086%-0.0055%) content of the pellets is not significant enough to affect the fertilizer quality of the pellets, so the predictive purposes of these graphs are not useful.

Response surfaces for ECCE (representing degradability) and durability demonstrate that pellet degradability and durability have opposing trends for each binder type (Figure 3) and show the effect of both moisture content and binder level on the response. In figure 3 the response is shown as a gray-scale contrast, with the lighter colors denoting higher responses. For each binder the graphs tend to show light colors on the ECCE graph (high degradability) where there are dark colors on the durability graph (low durability) and vice versa.

All of the nutrient RSD with the exception of one generated in this study, increase or decrease with binder level according to the nutrient levels in the binder and ash.

Figure 3: Durability and ECCE (representing degradability) response surface designs



In general, total and water soluble nutrient levels in the binders are higher than in the ash, except for water and total potassium for the bone meal, CDS, DDGS and total phosphorus for CDS and DDGS (Table 3). Nutrients with higher levels in the ash than in the binders (K and P) create pellets that decrease in nutrient content as binder level increases.

All other nutrient levels increase along with binder levels in the pellets. The RSD for water soluble inorganic nitrogen in bone meal pellets did not follow the expected trend. However, the values are essentially zero ranging from 0.0023% N to 0.0080% N and will have little effect on the fertilizer quality of the pellet.

Table 3: Nutrient and pH levels of the ash and binders

	pH	Total C (%)	Total N (%)	Water N (%)	Total P (%)	WaterP (%)	Total K (%)	WaterK (%)
ASH	13.03	1.86%	0.06%	0.0014%	7.61%	0.0005%	12.58%	8.63%
Bone meal	7.12	15.13%	1.54%	0.011%	14.16%	0.03%	0.06%	0.05%
CDS	3.51	24.52%	1.48%	0.028%	0.64%	0.56%	1.05%	1.02%
DDGS	4.63	48.91%	4.55%	0.029%	0.79%	0.66%	0.97%	1.08%

There is a significant difference in the water soluble and total nutrients in the ash, binders and pellets, especially in the case of phosphorus (Figure 2 and Table 3). We observed a minimal difference in potassium levels because potassium compounds are highly water soluble (Havlin, 1999). The total and water soluble N, P and K amounts in the ash were tested to determine a bioavailability range for nutrients in the ash which can be significantly affected by soil type and environmental conditions. Greenhouse and field trials should follow to make bioavailability determinations for the pellets.

Economic Analysis

An ideal binder inclusion rate would allow for durable and degradable pellets. Although it has a high degradability, due to its low durability, CDS does not make a good binder. Pellets with low DDGS inclusion had a durability of 63% and with low bone meal inclusion a durability of 78%. The ECCE or liming capacity of the pellets, which is dependent on the water degradability were 248 lb $CaCO_3$/ton pellets for DDGS and 121 lb$CaCO_3$/ton pellets for bone meal. Adding additional binder did not statistically change the durability or the degradability of the pellets. Since adding additional binder would cost more and not significantly affect the physical properties of the pellets, within the operating range tested, 15% inclusion rate of DDGS or bone meal would be more economical than including higher binder levels. An economic analysis of pelleting biomass ash was performed using assumptions listed in table 4. Current market prices were used for DDGS and bone meal. Because ash is currently considered a waste product so no cost was attributed to it. Table 5 shows the total cost per ton of pellets.

Table 4: Assumptions for economic analysis of ash pelleting

Category	Assumptions
Operating Labor	1.5 people, 24hrs day, 350 d/yr, $ 29.40/hr (inc. benefits)
Supervisory Labor	15% of operating labor (Brown, 2003)
Pellet production	2 tons/hr (McKay, 2008) 350d/yr
Electricity	200 hp, (McKay, 2008)
Bone meal	$225/ton (Hart, 2008), 15% inclusion rate
DDGS	$170/ton (Sauer, 2008), 15% inclusion rate
Feed pellet mill	$150,000.00 (McKay, 2008)
Conditioner and feeder	$ 50,000.00 (McKay, 2008)
Cooler	$ 30,000.00 (McKay, 2008)
Dust control system	$ 20,000.00 (McKay, 2008)
Auxiliary facilities	30% of capital (Brown, 2003))

Table 4 continued

Category	Assumptions
Maintenance and repairs	5% of fixed capital (Brown, 2003)
Operating supplies	15% of maintenance and repairs (Brown, 2003)
Loader	$ 1300/month (Buyer zone, 2008)
Interest rate	10%
Pelleting equipment	30% salvage, 15 yr life

Ash pellets with DDGS are less costly to produce than pellets with bone meal, however, the nutrient content of each vary. Ash pellets with bone meal have higher total P and total K levels and ash pellets with DDGS have higher total N and total C levels. Ash is most likely to be used for a potash and phosphate fertilizer substitute.

Table 5: Total cost of pelleting ash with DDGS and Bone meal binders

	DDGS Pellets	Bone meal Pellets
Capital cost	$ 1.26	$ 1.26
Direct labor	$ 22.05	$ 22.05
Supervisory labor	$ 3.31	$ 3.31
Electricity costs	$ 11.19	$ 11.19
Material cost	$ 25.50	$ 33.75
Auxiliary facilities	$ 0.38	$ 0.38
Maintenance	$ 0.06	$ 0.06
Operating Supplies	$ 0.01	$ 0.01
Loader	$ 0.93	$ 0.93
Total Cost ($/ton pellets)	$ 64.69	$ 72.94

Table 6 reports the cost of pellets per ton of phosphate equivalent comparing it to the price of commercial fertilizer to replace the phosphorus and potassium levels in the ash. In reality the available nutrient levels in the ash will vary, however, for cost estimation purposes, it is assumed that all the P and K in the pellets are available. Commercial fertilizer prices are based on MAPS (11-52-0) and Potash (0-0-60). When 15% bone meal is used as a binder, 5.4 tons of ash pellets are needed for one ton of phosphate equivalent. When 15% DDGS is used as a binder 6.8 tons of ash pellets are needed to equal one ton of pure phosphate.

Table 6: Pellet manufacturing cost per ton of P_2O_5 equivalent

	Pellet Cost	**Potash and phosphate equivalent fertilizer costs**	
	Ton of P_2O_5 equivalent	Spring 2007 Prices	Spring 2008 Prices
Bone meal (5.4 ton pellets)	$ 397.41	$ 1,322.95	$ 2,838.21
DDGS (6.8 ton pellets)	$ 441.52	$ 1,420.67	$ 3,033.66

DDGS and Bone meal have comparable physical properties (Figure 2), nutrient qualities (Figure 2) and production costs (Table 6). Binder market price, binder availability and handling issues will aid in determining which binder is appropriate for a specific pelleting facility. DDGS will not need to be ground but bone meal, depending on the production facility may need to be ground or sieved before it is used as a binder. Bone meal creates dust and permeates an odor while grinding and sieving. Availability of DDGS and bone meal will depend on the pellet production location. DDGS may be more available as its production is more widespread than bone meal.

Conclusions

Biomass ash, due to its high phosphorus and potassium content and liming capacity is a potential soil amendment. Greenhouse studies and field trials are needed to determine the bioavailability of nutrients in ash pellets. Condensed distillers solubles is not a viable binder due to the resulting low durability of the pellets. Binder level and binder type had a significant effect on the chemical and physical properties of the pellets. There is evidence of an interaction between binder type and binder level. We found that there is a general opposing trend for the degradability and durability of the pellets. DDGS or Bone meal inclusion rates of 15% created pellets with durability and degradability which were not statistically different than higher inclusion rates. Since increasing the binder level does not in general create higher degradability and durability, a low inclusion level could be chosen as it is more economically viable. Both the durability and degradability of the pellets depend on the moisture content used in the pellet formation. Response surface designs are useful tools for assessing the impact of the binder level and moisture content on the pellet properties. Utilization of biomass ash as a fertilizer is more sustainable and potentially more economical than synthetic fertilizer use. Pelleting biomass ash can create opportunities for nutrient recycling in biofuel production systems, reduce waste in the biofuel system, provide nutrients for crops and return carbon removed in harvested biomass back to the soil.

Acknowledgments

The authors would like to acknowledge Yilin Bian who provided guidance for initial ash compression trials and mixture formulation, Dr. Carl Bern who directed us to feed pelletizing technology, Dr. Ali Tabatabai and Dr. Stan Henning whose suggestions led to ash and binder procurement, Corn Plus Ethanol for providing the ash and CDS, Proliant Inc. for providing the bone meal, Lincoln Way Energy for providing the DDGS, the Iowa State University (ISU) Center for Crop Utilization Research (CCUR) for the use of their feed pellet mill, Mark Reuber at CCUR for his assistance with pelleting, the undergraduate research assistants who assisted with producing ash pellets and physical testing, Dr. Matt Liebman and Dr. Raj Raman for their suggestions and guidance regarding the experimental design, Brian Hill at the ISU Soil Testing Lab for his guidance regarding chemical characterization of ash and Anna Peterson and Dr. Phillip Dixon at ISU Statistical Consulting Services for their assistance with the experimental design and statistical analysis.

This material is based upon work supported by the National Science Foundation under Grant No. 0424700. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

Agrielectric. Rice hull ash. <http://www.agrilectric.com/ricehullash.php> (accessed 20.3.08).

Anex, R.P., Lynd, L.R., Laser, M.S., Heggenstaller, A.H., Liebman, M. 2007. Potential for enhanced nutrient cycling through coupling of agricultural and bioenergy systems. Crop Sci. 47, 1327–1335.

AOAC Standard. 2007. Agricultural liming materials. AOAC, Gaithersburg, MD.

ASAE Standard S269.4. 1996. Cubes, pellets, and crumbles- definitions and methods for determining density, durability and moisture content. ASABE. St. Joseph, MI.

Begole, B.F. 1970. Charcoal - from slums to affluency. The Professional Geographer 22, 185-188.

Bland, A.E., Cox, R.K., Lichty, E.R., Rowen, A.R., Schumann, R.A. 1992. Pelletizing Ash. United States Patent number 5137753.

Brown, R.C. 2003. Biorenewable Resources. Iowa State Press. Ames, IA.

Buyer zone. 2008. Skid steer pricing: Skid Steer Loader Buyer's Guide. Available at: http://www.buyerzone.com/industrial/steer_loaders/buyers_guide6.html. accessed on 22 March 2008.

CVEC. 2006. CVEC to convert to biomass power. Ethanol Producer Magazine. March Issue.

Eliot, J. 1934. Upon Field Husbandry and Other Papers 1748-1762. p. 29. ed. by Carman, H.J, and Tugwell, R.G. Columbia University Press.

EPA Method 3050B. 1996. Acid digestion of Sediments, Sludges, and soils.

Etiegni, L., Campbell, A.G., and Mahler, R.L. 1991a. Evaluation of wood ash disposal on agricultural land I. Potential as a soil additive and liming agent. Commun. in Soil Sci. Plant Anal. 22, 243-256.

Etiegni, L., Mahler, R.L., Cambell, A.G. Shafii, B., 1991b. Evaluation of wood ash disposal on agricultural land. II. Potential toxic effects on plant growth. Commun. In Soil Sci. Plant Anal. 22, 257-267.

Hanrahan, T.J., 1984. Effect of pellet size and pellet quality on pig performance. Anim. Feed Sci. and Technol., 10, 277-283.

Hart, Dave. Personal communication. Hormel Foods, Austin, MN. 15 April 2008.

Havlin, J.L, Beaton, J.D., Tisdale, S.L., Nelson, W.L., 1999. Soil Fertility and Fertilizers, An Introduction to Nutrient Management. Sixth edition. Prentice Hall. Upper Saddle River, New Jersey.

Huang, H., Cambell, A.G., Folk, R., Mahler, R.L., 1992. Wood ash as a soil additive and liming agent for wheat: field studies. Commun. Soil Sci. Plant Anal. 23, 25-33.

Huang, W. Z. Schoenau, J.J. 1998. Fluxes of water soluble nitrogen and phosphorus in the forest floor and surface mineral soil of a boreal aspen stand. Geoderma 81, 251-264.

Kenny, M. 2005. Optimising Nutrient Intake. Aviagen Technical Article. <http://www.aviagen.com/output.aspx?sec=2674&con=3200&siteId=2&dupOf=3190> (accessed 20.3.08).

Khuri, A.I, Cornell, J.A., 1987. Response Surface Designs and Analyses. Marcel Dekker Inc. ASQC Press, New York, New York.

Kotrba, R., 2006. The red-hot sands of Winnebago. Ethanol Producer Magazine. June Issue.

Laird, D.A. 2008. The charcoal vision: A win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. Agronomy Journal. 100, 178-181.

Lehmann, J. 2007. A handful of carbon. Nature. 447, 143-144.

Mckay, Eric. Personal communication. Roskamp California Pellet Mill, Crafordsville, IN. 15 April 2008.

Morey. R. 2007. Generating Electricity with Biomass Fuels at Ethanol Plants http://www.biomasschpethanol.umn.edu/ProjectReports/XcelRD-56ProgressReportFive4-12-07.pdf (accessed 20.3.08).

Mozaffari, M., Rosen, C.J., Russelle, M.P., Nater, E.A., 2000a. Corn and soil response to application of ash generated from alfalfa stems. Soil Science. 165, 896-907.

Mozaffari, M., Rosen, C.J., Russelle, M.P., Nater, E.A. 2000b. Chemical characterization of ash from gasification of alfalfa stems: implications for ash management. J. Environ. Qual. 29, 963-972.

Mozaffari, M., Russelle, M.P., Rosen, C.J, Nater, E.A., 2002. Nutrient supply and neutralizing value of alfalfa stem gasification ash. Soil Sci. Soc. Am. J. 66, 171-178.

Nilles, D. 2007. Creating an energy island. Ethanol Producer Magazine. February Issue. <http://ethanolproducer.com/article.jsp?article_id=2721> (accessed 26.11.07).

Patterson, S. J. Acharya, S. N. Bertschi A. B. Thomas, J. E., 2004. Application of wood ash to acidic boralf soils and its effect on oilseed quality of canola. Agron. J. 96, 1344-1348.

Pietsch, W. 2005. Agglomeration in Industry: Occurrence and Application. Volume 1. Wiley-VCH. Weinheim, Germany.

Price, H. 1938. Apparatus for treating finely divided powders. United States Patent number 2127137.

RHR, Rice Husk Resources. Ultrashield. <http://www.rha.co.in/products.html>. (accessed 20.3.08).

Rosentrater, K.A., 2007, Can you really pellet DDGS? Distillers Grains Quaterly-3rd quarter issue. <http://www.distillersgrainsquarterly.com/article.jsp?article_id=1212&article_title=Can+You+Really+Pellet+DDGS%3F> (accessed 20.3.08).

Sarenbo, S.L. and Claesson, T. 2004 Limestone and dolomite powder as binders for wood ash agglomeration. Bull Eng Geol Env. 63, 191-207.

Sauer, Ryan. Personal communication. Hawkeye Gold. Ames, IA. 15 April 2008.

Steenari, B.M., Marsic, N., Karlsson, L.G., Tomsic, A., Lindquist, O., 1998. Long-term leaching of stabilized wood ash. Scad. J. For. Res. Suppl. 2, 3-16.

Stehouwer, R. C. Warren D. A. and Sutten P. 1999. Acidic soil amendment with a magnesium-containing fluidized bed combustion by-product. Agron J. 91, 24-32.

CHAPTER 3

Ethanol Co-product Allocation: Distillers Grains in Cattle Diets

Edwards, K. A.(1), Anex, R. P.(1)*

A paper to be submitted to *The Journal of Biofuels, Bioproducts and Biorefining*

Abstract

The allocation of co-products in corn grain ethanol production significantly influences net energy system calculations. Distillers grains (DG), are a co-product derived from dry grind ethanol production and are used primarily in cattle feed rations. DG provide both energy and protein to the animal's diet. Ethanol co-product credit estimates are typically determined by using a fixed cattle feed component displacement ratio and DG inclusion rate. In practice, feed components displaced by DG vary in cattle diets. For this reason, we have calculated co-product credits based on the actual feed components displaced. We have determined that the co-product credit is highest at low DG inclusion rates in cattle diets. When DG inclusion levels are 15%-40% the co-product credit for DG ranges from 2.2 MJ/L to 4.3MJ/L depending on the type of DG added to the animal diet and the type of feed component displaced. Corresponding net energy calculations for a typical dry grind ethanol system range from 2.7 MJ/L to 4.8 MJ/L. As the ethanol industry matures, the number and variety of ethanol co-products will likely increase. The appropriate co-product credit and corresponding net energy value for any given ethanol plant will vary depending on the suite of co-products the ethanol plant generates and their range of uses.

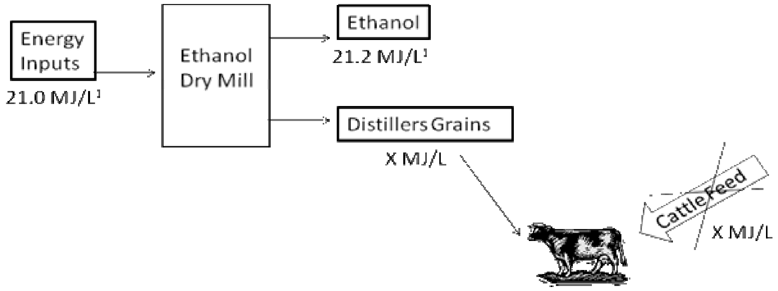
*Corresponding Author (rpanex@iastate.edu)

(1)Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50010

Introduction

Co-product allocation and the distribution of production energy between products and co-products, is an essential component when determining the net energy of biofuel production systems. Farrell et al.[1] found through sensitivity analysis that the co-product credit is the most significant factor in ethanol net energy calculations. In corn dry grind ethanol production there are two major products, ethanol and distillers grains (DG) which are commonly used in cattle feed rations. Because both the ethanol and DG are useful products, the total production energy is allocated between the ethanol and DG rather than solely attributed to the ethanol (Figure 1). One type of allocation, the displacement method approach, determines the energy required to produce the product that is displaced by the co-product and attributes this energy to the co-product. In ethanol production DG are replacing animal feed. In the displacement approach the energy required to produce the DG is equated to the energy required to produce the displaced animal feed (Figure1). This value is then used as an energy co-product credit in the system net energy calculation. The amount of feed displaced in the cattle diet depends on the amount of DG fed. In this study we calculate the ethanol co-product credit for multiple inclusion levels of dried (DDGS) and wet distillers grain with solubles (WDGS) in cattle diets.

Figure 1: Illustration of distillers grain co-product allocation in ethanol production



Distillers grains are high in protein and fiber content. Approximately two thirds of all DG produced in the USA are fed to cattle.[2] The DG consist of the residual corn after starch is removed for ethanol production. After ethanol distillation, whole stillage, the bottoms of the distillation column, are centrifuged to produce a liquid portion called thin stillage, and solid portion termed wet distillers grains (WDG). In dry grind plants, the thin stillage is condensed creating condensed distillers solubles (CDS), which is added to the WDG during a drying process, resulting in the production of distillers dried grains with solubles (DDGS).

Energy, resource use and emissions inventories can be allocated on the basis of the co-product mass, caloric content, market value and displacement value. [1,3-5] Typically, ethanol net energy studies that include co-product allocation use the displacement method to allocate the energy credited to distillers grains (Table 1). The displacement method determines energy required to create co-products by calculating the life cycle energy used to create the product that is displaced by the co-product.

Table 1: Coproduct credit allocation

Author	**Credit (MJ/L)**	**Basis**	**Feed Replaced**
Kim and Dale[6]	4.40	Expansion	Corn, soybean meal
Shapouri et al.[5]	3.70	Displacement	Soybean meal
Shapouri et al.[7]	7.31	Mass	
Graboski[8]	4.13*	Displacement	Corn, soybean meal and corn oil
Wang as cited in Farrell[1]	4.04	Displacement	Corn, soybean meal

*includes dry and wet milling co-products in credit

Multiple studies have estimated ethanol co-product credits using the displacement method.[4,5,8] In 2002, Shapouri et al.[5] used the displacement method assuming DG replace soybean meal and reported a co-product credit of 3.7 MJ/L. In 2004, Shapouri et al.[7] redid the analysis using mass allocation and reported a value of 7.31 MJ/L. The displacement method is a more meaningful approach than mass allocation because the usefulness of the distillers grains and ethanol are not necessarily proportional to their mass. The displacement method considers what the co-product will be used for and the energy saved by no longer creating that displaced product. The co-product credit for corn dry grind ethanol production can be estimated with the displacement method by determining the amount of protein supplement and corn displaced in a cattle diet by feeding distillers grains. The life- cycle energy required to produce the displaced corn and protein in the cattle diet is designated as an energy credit to the ethanol process.

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model uses the displacement method and assumes that DDGS displaces corn and soybean meal (SBM) in cattle diets.[4] A constant feed displacement ratio of 1 lb DDGS displaces 1.077 lbs of corn and 0.85 lbs SBM is assumed.[4,9] Kim and Dale[6] also assume DDGS displace corn and SBM in cattle diets and use the same displacement ratios as Wang.[4] Kim and Dale[6] use a “multi-expansion” allocation approach. This approach includes additional displacement to determine the production energy of soybean meal by allocating the energy in soybean meal and soybean oil production. Wang,[9] Sheehan et al.[10] and Graboski[8] instead use mass allocation to determine the production energy of SBM.

To estimate the production energy required for soybean meal, Kim and Dale[6] first determine the total energy for soybean processing which produces both soybean meal and soy oil. They then assume the production energy for soybean oil is equivalent to the production energy for corn oil. Their estimates for corn oil production energy requirements are determined by allocating energy use in corn wet milling. This allocation is determined from the energy required to produce corn gluten meal (CGM) and corn gluten feed (CGF), both of which are wet milling co-products. Kim and Dale assume CGM and CGF are used to displace corn and urea in animal diets. Once the production energy for corn oil is estimated and equated to the production energy of soybean oil, they determine the production energy for soybean meal by subtracting the soybean oil production energy from the total soybean processing production energy.[6]

The energy and protein provided by DG displace corn and protein supplements in cattle rations. Because both energy and protein are displaced there is an energy and protein portion of the co-product credit. The energy and protein value of DG to cattle decrease as inclusion rates increase, thus, a constant replacement ratio is not appropriate to determine the quantity of displaced feed. The variable energy and protein value results in a variable co-product credit. The amount of distillers grain fed to cattle varies from 15%-40% of the total feed dry matter intake (DMI). The percent added to feed depends upon its purpose—either as an energy or protein source. Inclusion of DG in cattle diets at levels below 15% is intended to provide protein. At higher levels, after protein demands have been met, DG serve as an energy source and excess protein is excreted by the animal.[11] The animal's health and beef quality are not significantly affected when cattle are fed distillers grains up to 40% of their DMI.[12]

At higher DG inclusion rates in cattle rations excess protein is consumed but cannot be utilized by the animal, so passes through and is eliminated. This excess protein should not be included in the co-product credit because it is not displaced. Graboski[8] considers the limited protein value of DG in cattle diets in his co-product credit calculation. Instead of using a fixed displacement ratio like Wang[9] and Kim and Dale[6] he estimates actual feed displaced per head of cattle by comparing a diet with distillers grains and without distillers grains. In his estimate he uses a fixed inclusion rate of DG. In practice, however, multiple levels of DG are incorporated into cattle diets. We have estimated the effect of variable inclusion rates on the resulting co-product credit.

Materials and Methods

Dry grind ethanol co-product credit consists of a protein and energy portion. The protein and energy credits are determined by estimating the amount of protein and energy displaced in cattle diets by feeding DG and then multiplying this by the life-cycle production energy of the feed component displaced. We calculated the energy and protein portion of the co-product credit for DDGS and WDGS. The protein credit was calculated for urea and soybean meal. Multiple life-cycle production energy values for corn,[1,5,8,9] urea,[6,8,13] and soybean meal[8,10] were averaged and used for the life-cycle production energy of the displaced cattle feed components (Table 2).

The energy feeding value of distillers grains changes with inclusion rate (Table 3).[14] The energy portion of the co-product credit was determined from these feeding values (equation 1).

Table 2: Life-Cycle Energy of Corn, Urea and Soybean Meal Production

Source	Corn (MJ/kg)	Urea (MJ/kg)	SBM (MJ/kg)
Shapouri et al.[5]	2.39		
Farrell et al.[1]	2.16		
Wang[9]	2.62		
Graboski[8]	2.14	26.1	7.47
Sheehan et al.[10]	---		6.86
Kim and Dale[6]		24.0	
Kobayashi and Sago[13]		22.3	
Average	**2.33**	**24.1**	**7.17**

Distillers grains production rates, DG energy feeding values, corn life-cycle production energy and ethanol yield were used to determine the energy credit (equation 1). Distillers grain production, ethanol yield and cattle dry matter intake were assumed to be 0.3 kg/kg_{corn},[15] 0.396 L/kg_{corn},[1] 9.55 kg/day/hd[15].

Table 3*: Energy feeding value of distillers grains
(kg corn replaced/kg distillers grains fed)

Inclusion Level	WDGS	DDGS
15%	1.44	1.37
20%	1.42	1.23
25%	1.39	1.14
30%	1.37	1.07
35%	1.34	1.02
40%	1.31	1.00

*adapted from Klopfenstien et al.[14] using linear (WDGS), $R^2 = 0.9889$ and quadratic (DDGS), $R^2 = 0.9992$ extrapolation

$$\text{Energy Credit} = \frac{\text{DG Production}\,(\text{kg}_{\text{DG}}/\text{kg}_{\text{corn}})}{\text{EtOH Yield}\,(\text{L}/\text{kg}_{\text{corn}})} * \text{DG Feeding Value}\,(\text{kg}_{\text{Corn}}/\text{kg}_{\text{DG}}) * \text{Corn Production Energy}\,(\text{MJ}/\text{kg}_{\text{corn}}) \qquad (1)$$

The protein portion of the credit was calculated by assuming DG displaces either soybean meal or urea. Inclusion rates of urea and soybean meal were estimated using an Excel™-based model, Beef Ration and Nutrition Decisions Software (BRaNDS), from the Iowa Beef Center, based on National Research Council feeding recommendations.[16] Diets were balanced for appropriate energy and protein levels using corn, urea and forage in one diet and corn, soybean meal and forage in another. Because protein requirements in cattle rations change with cattle weight, two diets were assumed for finishing cattle--one for cattle weighing 341kg-455kg and another for cattle weighing 455kg-614kg. The inclusion rates of urea and soybean meal were averaged from the inclusion rates of these diets. The average inclusion rates estimated were 0.9% DMI for urea and 4.8% DMI for soybean meal. The amount of urea or soybean meal displaced in cattle diets at WDGS and DDGS inclusion rates of 15%, 20%, 25%, 30%, 35% and 40% of cattle DMI and the life-cycle production energy of the displaced feed were used to determine the protein credit (equation 2). To determine the protein supplement displaced relative to ethanol production, the DG production rate, DG included in cattle diets, protein supplement traditionally fed and ethanol production were used (equation 2). This estimate of the amount of protein supplement displaced was multiplied by the life-cycle production energy of the protein supplement, to determine in the protein credit (equation 3).

$$\text{Protein Supplement Displaced (kg/L}_{\text{EtOH}}\text{)} = \frac{\text{DG Production (kg/bucorn)}}{\text{DG Fed (kg/hd/day)}} * \frac{\text{Supplement Fed (kg/hd/day)}}{\text{EtOH Production (L/bucorn)}} \quad (2)$$

$$\text{Protein Credit (MJ/L}_{\text{EtOH}}\text{)} = \text{Protein Supplement Displaced (kg/L}_{\text{EtOH}}\text{)} * \text{Production Energy (MJ/kg)} \quad (3)$$

The co-product credit was then used to determine the net energy of ethanol using life cycle input energy values from a representative ethanol plant (equation 4). The life-cycle input energy of the system and the energy exiting the system in the ethanol and co-product produced were used to determine the net energy.

$$\begin{aligned} &\text{Net Energy} = \text{Input Energy- EtOH}_{\text{LHV}} - \text{Coproduct credit} \\ &\text{Net Energy} = 20.71 \text{ MJ/L} - 21.20 \text{ MJ/L} - \text{Coproduct credit} \end{aligned} \quad (4,^{1})$$

Results and Discussion

Low DG inclusion rates in cattle diets result in the highest ethanol co-product credit (Figure 2). Conversely, high DG inclusion rates provide a low co-product credit, resulting in low net energy values. The co-product credit varies depending upon the type of protein displaced and the amount and type of distillers grains incorporated into the diet.

Protein Credit

In this study, the protein displaced is assumed to be either soybean meal (SBM) or urea. The credit for SBM is greater than that for urea (Figure 2). The protein credit ranges from 0.4 MJ/L to 1.1MJ/L for urea and 0.6 MJ/L to 1.7 MJ/L for SBM. The protein portion of the co-product credit is higher when SBM is displaced then when urea is displaced, thus the total co-product credit for Corn + SBM is higher than for Corn + Urea. Because cattle protein requirements are assumed to be met at 15% DG inclusion rates, the amount of displaced protein is the same per animal regardless of whether DDGS or WDGS is fed. Therefore the protein portion of the co-product credit for wet and dry DG is the same.

Energy Credit

The energy credit from the displaced corn is based upon the energy feeding value of the DG compared to corn and is higher for WDGS than DDGS. DDGS have a lower energy value than WDGS due to volatilization of nitrogen in the form of ammonia and denaturing of proteins occurring during the drying process. The energy portion of the co-product credit, ranges from 1.8 MJ/L to 2.4 MJ/L for DDGS and 2.3 MJ/L to 2.5 MJ/L for WDGS.

Total Credit

The total co-product credit for DDGS, consisting of both the energy and protein credit is estimated to range from 2.4 MJ/L to 4.2 MJ/L for SBM+corn and 2.2 MJ/L to 3.5 MJ/L for urea+corn (Figure 2). The higher energy value of WDGS, results in a higher energy portion of the co-product credit when WDGS is fed. The total WDGS co-product credit for SBM+corn ranges from 3.0 MJ/L to 4.3 MJ/L and 2.7MJ/L to 3.7 MJ/L for urea+corn.

The co-product credits we calculated in this study were substituted for the co-product credit in Farrell et al.[1] “Ethanol Today” estimate to calculate the net energy associated with each credit (Table 4). The net energy of ethanol varies by 44% depending on DG cattle feeding rates, type of DG fed and the type of protein supplement displaced by DG (Table 4).

Figure 2: DDGS Co-product Credit

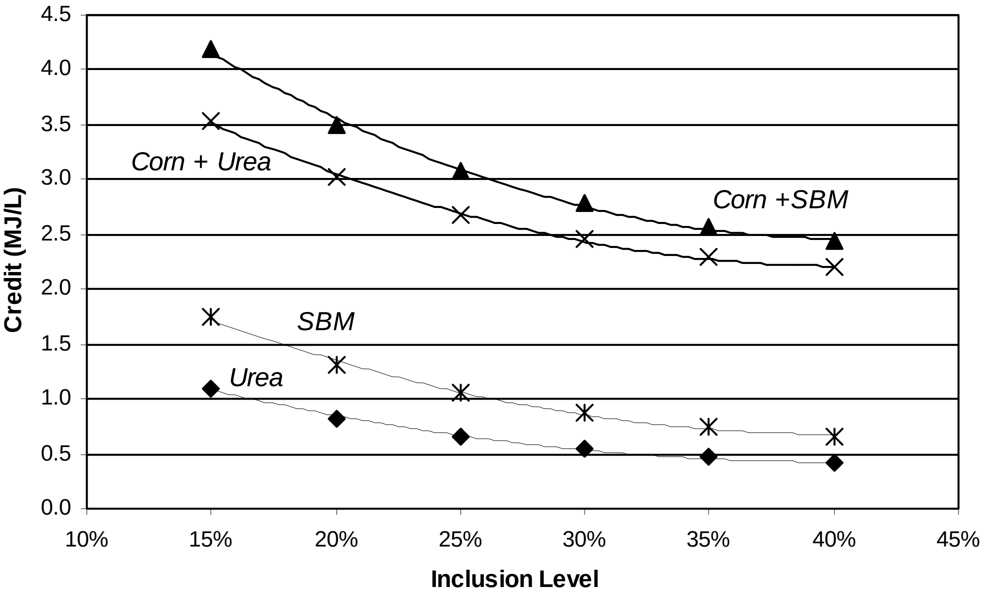


Table 4: Net Energy (MJ/L) range with DG inclusion levels of 15-40%

	WDGS	DDGS
Corn + Soy	3.5-4.8	2.9-4.6
Corn +Urea	3.2-4.2	2.7-4.0

The lowest net energy values occur at the highest DG inclusion levels in cattle diets. At low DG inclusion levels more cattle are fed with the distillers grains produced from a facility resulting in a higher co-product credit and higher system net energy. Farmers usually chose their feed based on cost. With current corn prices high, it is less expensive for farmers to supplement DG for corn in cattle diets as an energy source. Despite 40% DG inclusion rates in cattle diets being the common acceptable limit due to the potential negative effects on growth rate, carcass quality and meat quality,[17] feedlots feed up to 60% distillers grain.[18] At DG inclusion levels above 40% the co-product credit will be lower than estimated here. At high DG inclusion levels the net energy value is substantially lower than Farrell et al.[1] "Ethanol Today" 4.6 MJ/L estimate of the net energy of ethanol production.

Conclusion

Energy co-product credits for corn dry grind ethanol production depend on the cattle feed that is replaced by the DG. The credit will vary with the type and rate of DG fed to cattle and the type of protein replaced in cattle diets. We estimate the energy credit for DG ranges from 2.2 MJ/L to 4.3MJ/L. Energy allocations to co-products will significantly effect system net energy calculations. The net energy of ethanol production for a representative ethanol plant ranges from 2.7 MJ/L to 4.8 MJ/L for DG inclusion rates of 15%-40%. In the future, dry grind ethanol plants are expected to begin producing a greater variety of co-products. Integration of feedstock and co-product fractionation technology will help increase the variety of value-added products. This increase of co-products and their uses will add complexity to the challenge of determining the co-product credit for a specific ethanol facility.

Acknowledgements

The authors would like to acknowledge Dr. Garland Dahlke at the Iowa Beef Center for his assistance with protein level determination in cattle diets, Dr. Alan Trenkle and Dr. Jim Russell in the Department of Animal Science at Iowa State University for their assistance regarding the feeding value of distillers grains, and Dr. Chad Hart at the Center for Agricultural and Rural Development and Charlie Staff, President of the Distillers Grains Research Council for providing information regarding the use of distillers grains in cattle diets.

References

1. Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM, Ethanol can contribute to energy and environmental goals. *Science* 311:506 (2006).
2. Hart C, Center for Agricultural and Rural Development. Iowa State University. Personal communication. February 21, 2008.
3. Curran MA, Co-Product and input allocation approaches for creating life cycle inventory data: a literature review. *Int J LCA.* Special issue 1: 65-78. (2007)
4. Wang M, GREET 1.5 – Transportation Fuel Cycle Model, Volume 1: Methodology, Development, Use and Results. Argonne National Laboratory, Illinois, USA (1999).
5. Shapouri H, Duffield DA, Wang M, The energy balance of corn ethanol: an update. USDA Agricultural Economic Report Number 814 (2002).
6. Kim S, Dale BE, Allocation procedure in ethanol production system from corn grain. I. System expansion. *Int J LCA* 7(4): 237-243 (2002).
7. Shapouri H, McAloon A, The 2001 net energy balance of corn-ethanol. USDA report. Presented at the Corn Utilization and Technology Conference, June 7-9, 2004, Indianapolis, IN. Available online at: http://www.usda.gov/oce/reports/energy/net_energy_ balance.pdf. Accessed 20 March 2008. (2004).
8. Graboski MS, Fossil energy use in the manufacture of corn ethanol. Prepared for the National Corn Growers Association. (2002).
9. Wang M, Greet 1.8a – The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. Argonne National Laboratory, Illinois, USA. (http://www.transportation.anl.gov/software/GREET/) (2007).

10. Sheehan J, Life cycle inventory of biodiesel and petroleum diesel for Use in an urban bus. Prepared by National Renewable Energy Laboratory (1998).
11. Erickson GE, Klopfenstein TJ, Adams DC, Rasby RJ, Utilization of corn co-products in the beef industry: feeding of corn milling co-products to beef cattle. 2nd Ed. University Nebraska Lincoln and Nebraska Corn Board. (2007)
12. Tjardes K, Wright C, Feeding corn distiller's co-products to beef cattle. South Dakota State University Extension Service. ExEx 2036 (2002).
13. Kobayashi H, Sago R, A Study on life cycle assessment of energy consumption and CO2 emissions in the manufacturing and transportation processes of nitrogen and phosphate fertilizers. *Japanese Journal of Farm Work Research.* 36(3):141-151 (2001).
14. Klopfenstien TJ, Erickson GE, Bremer VR, Board Invited Review: Use of distillers byproducts in the beef cattle feeding industry. Published Online in *Journal of Animal Science*. http://jas.fass.org/cgi/content/abstract/jas.2007-0550v1. (2007)
15. NCGA (National Corn Growers Association). http://ncga.com/livestock/PDFs/DistillersGrainsBooklet.pdf (2008).
16. BRaNDS (Beef Ration and Nutritions Decisions Software). Iowa State University Extension. Available online at: http://www.iowabeefcenter.org/content/software _software_brands.html. Accessed 30 March 2008. (2008).
17. U.S. Grains Council, Use of DDGS in beef diets, DDGS user handbook. http://www.grains.org/galleries/DDGS%20User%20Handbook/02%20-%20Use%20of%20DDGS%20for%20Beef%20Cattle.pdf.
18. Trenkle A, Value of modified wet distillers grains in cattle diets without corn. Iowa Beef Center. A.S. Leaflet R2184 (2007).

CHAPTER 4

An Integrated Beef-Ethanol Production System: Net Energy, Nutrient Concentration and Water Consumption

Edwards, K. A.(1), Anex, R. P.(1)*

A paper to be submitted to *The Journal of Biobased Materials and Bioenergy*

Abstract

The evolving ethanol industry is creating opportunities for obtaining higher net energy values than possible in current corn dry grind ethanol production, through process improvements and the integration of multiple renewable energy technologies.[1] One biorefinery configuration integrates a corn dry grind ethanol plant, a cattle concentrated animal feeding operation, and waste digesters. This system is designed to improve the overall energy balance by processing cattle manure and thin stillage--a byproduct from ethanol production in bioreactors--to power the ethanol plant, and feeding wet feed supplements from the ethanol plant to the cattle. This integration improves energy efficiency but causes key resource concerns because of localized nutrient concentration and water consumption. In this study, we found the net energy of a hypothetical system- a 94.6 x 10^6 liters/year (25 million gallon/year) ethanol plant and a 17000 head cattle concentrated animal feeding operation- to be 13.71 MJ/liter compared to 4.6 MJ/liter for a non-integrated corn dry grind ethanol plant.[1] The integrated system requires twenty-eight thousand hectares for spreading the reclaimed nutrients from the manure and thin stillage and consumes 7.1 $\text{liters}_{\text{water}}/\text{liter}_{\text{EtOH}}$, compared to 3.5 $\text{liters}/\text{liter}_{\text{EtOH}}$ in a conventional system.[2] Nutrients can be extracted at several points in the system and can potentially be returned to the crop fields as soil amendments or fertilizers. Utilizing

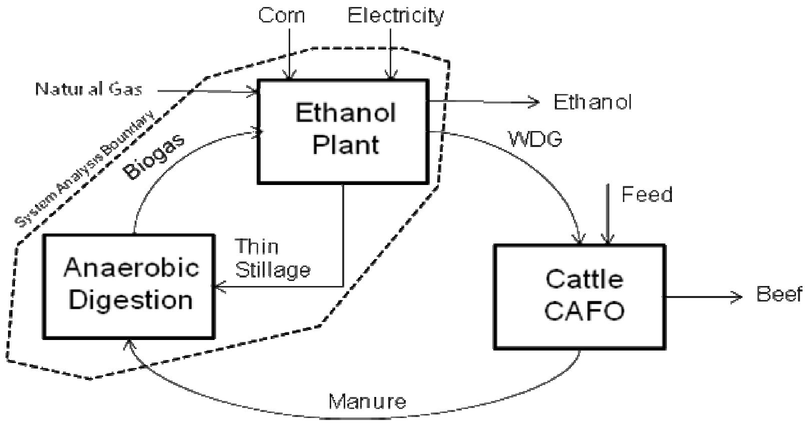
the nutrients from this integrated biofuel production system to close nutrient cycles, mimicking natural ecosystems, will increase the overall system sustainability.

*corresponding author (rpanex@iastate.edu), 3202 NSRIC, Ames, IA 50011, 515-294-6576
Fax: 515-294-4250
(1)Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50010

Introduction

In the evolving ethanol industry, process improvements and integration of multiple renewable energy technologies are creating opportunities for higher net energy values than possible in current corn dry grind ethanol production.[1] One biorefinery configuration integrates an ethanol plant, cattle concentrated animal feeding operation (CAFO), and waste digesters (Figure 1). This integration increases the system net energy by digesting waste streams to produce process heat for the plant and eliminating the use of dryers for distillers grains--a co-product from ethanol production commonly blended in cattle feed rations.

Figure 1: Energy flows in integrated Beef-Ethanol system



Distillers grains are a co-product from ethanol production and are the residual from corn kernels after starch is removed for ethanol fermentation. Following distillation, most of the water is removed from the non-fermentable solids or whole stillage that remains in the bottom of the distillation column by centrifugation. This creates wet distillers grains (WDG), the solids portion of the whole stillage and thin stillage, the liquid portion. In a traditional ethanol plant, WDG is dried and the thin stillage condensed to create solubles. These are added to the WDG during the drying process to create distillers dried grains with solubles (DDGS). Because the DDGS has been dried it can be stored and shipped long distances for use in animal feed rations. But drying and transporting this grain utilizes a significant amount of energy. In an integrated beef-ethanol production system, displacing natural gas use with bio-gas, eliminating the need for drying distillers grains and reducing the transport distance of distillers grains creates an opportunity to improve the net energy of ethanol production.

Although integrating ethanol production and an anaerobic digestion system and cattle CAFO has the potential to increase ethanol net energy as compared to stand alone corn dry grind ethanol plants, increased water consumption and nutrient concentration due to the co-location of the processes creates key resource issue concerns. Utilizing thin stillage for methane production rather than recycling it increases water use in the ethanol plant. Co-locating a CAFO with the ethanol plant will increase the amount of water used in one location instead of dispersing water use over multiple locations and aquifers. Essential plant nutrients such as nitrogen, phosphorus and potassium are unutilized in the ethanol production process, but exit in the distillers grains, concentrating in the waste digestion sludge. Concentrated nutrients could disrupt agronomic nutrient cycles if these nutrients are not returned to farm fields. Their return would help close otherwise open nutrient cycles. The economic and environmental sustainability of an ethanol production system can be increased by capturing these nutrients and applying them to crop land as fertilizer. In this study, we have estimated the net energy, water consumption and land application area required to apply nutrients concentrated for an integrated beef-ethanol production system.

Materials and Methods

We modeled a system which integrates a 94.5 x 10^6 liters/year (25 million gallons/year) ethanol plant; a 17,000 head cattle CAFO where the cattle consume 40% WDG in their diets, and an anaerobic digester. A WDG inclusion rate of 40% is the common acceptable limit due to the potential negative effects on animal growth rate, carcass and meat quality that can occur from overfeeding distillers grains.[3] The cattle CAFO was sized so all the wet distillers grains were consumed on a single site. The system boundary is the ethanol plant and anaerobic digester (Figure 1). In our net energy calculation we did not account for the production energy required for cattle feed or an energy credit for the beef produced. Therefore, the net energy calculation is a net energy of ethanol production, not the entire beef-ethanol production system. This is done so the results will be easily comparable to a stand alone dry grind ethanol plant. If the CAFO was included in the system boundary it would include beef production and ethanol production and this is not easily comparable to ethanol production alone.

Net Energy of Ethanol Production

The net energy of ethanol production varies with the production method. Net energy is the amount of energy produced from the system per unit of product. The ethanol net energy includes the energy required for corn production and transport, process electric power, ethanol transport, supplemental process heat, a credit for the ethanol energy content, and ethanol co-products (Figure 1).[4] An energy cost is also assumed for the manure since it is outside the system boundary. This cost is calculated by determining the energy produced through AD digestion of the manure.

To estimate the net energy of this system, we calculated thermal energy production including an energy cost for manure, fossil fuel inputs, and a credit for the energy content of wet distillers grains (WDG).

Thermal Energy Production

One-third of the total 10.3 MJ/liter[4,5] of thermal energy demand of a traditional dry grind ethanol plant is for drying distillers grains and condensing thin stillage.[5] Thus, eliminating the condensers and dryers in an integrated beef-ethanol production system reduces the thermal energy requirement to 6.9 MJ/liter. Producing methane onsite from thin stillage and manure further reduces the external fossil energy needed. In this study, we have used methane production potentials from thin stillage and an energy cost for methane production from manure to determine the total process heat produced onsite and the additional supplemental natural gas required.

Little information exists in the literature regarding thin stillage production. Kwiatowski et al.[6] estimate water usage in a 150 x 10^6 liters/yr (40 million gallons/year) facility and include thin stillage production to be 4.72 liters/liter$_{EtOH}$, Rasmussen et al.[7] report 5.54 liters/liter$_{EtOH.}$ Corn Plus Ethanol in Winnebago, MN reports a thin stillage production of 4.50 liters/liter$_{EtOH}$.[8] We averaged these data points and assumed thin stillage production of 4.97 liter/liter$_{EtOH}$. We used the volatile solids (VS) content of thin stillage (Table 1) and the chemical oxygen demand (COD) of manure to estimate methane production (Table 2).

Table 1: Methane Generation from thin stillage

Thin Stillage (using VS)	
Methane conversion[9] (m^3 CH_4/kg VS_{added})	0.5
Thin stillage VS content[9] (kg/liter)	0.07
Thin stillage generation (liters/yr)	470×10^6
Methane Production (MJ/yr)	**490×10^6**

Table 2: Energy cost for manure: methane production from cattle manure

Cattle Manure (using COD)	
COD* (kg/hd/d)[10,11]	2.16
Methane/kgCOD[10]	0.39
Methane Production (m^3/hd/d)**[10]	0.23
Feedlot size (animals)	17000
Methane Production (MJ/yr)	**49×10^6**

*averaged value

**based on 90% manure collection and 30% COD conversion efficiency

Fossil Energy Inputs

Eighty-three percent of the thermal energy needs for an integrated ethanol production facility are provided by methane produced on site, 75% of the thermal energy produced is from thin stillage (Table 3). An energy cost for using the manure is estimated since it is out of the system boundary. This cost is 49×10^6 MJ/yr (Table 2). Because the thermal energy produced does not meet the demands of the thermal energy required, natural gas is supplemented to provide the remaining 112×10^6 MJ/yr of process heat required for production.

Table 3: Ethanol plant thermal energy production and consumption

Thermal Energy (LHV)	(MJ/yr)
Total Consumed*	650×10^6
Methane from manure	49×10^6
Methane from Thin Stillage	490×10^6

*based on 6.88 MJ/liter[4,5], a 33% reduction from a traditional plant which converts WDG to DDGS[5]

Fossil energy is consumed in multiple steps during the ethanol production process. Total fossil energy inputs for the integrated system are approximately 7.65 MJ per liter of ethanol produced (Table 4).

Table 4: Fossil Energy Inputs*

Inputs	Estimate (MJ/liter)
Corn production energy[1,12-15]	5.86
Corn transport energy[12-14]	0.58
Electricity[2]	0.05
Ethanol Transport[1,12-15]	0.39
Supplemental Natural gas	0.77
Total	**7.65**

*values averaged from listed sources

WDG Co-product credit

An ethanol co-product credit for WDG was determined using the co-product allocation displacement method described in chapter 3 of this thesis, substituting WDG production rate and feeding value for DDGS. We assumed that the WDG displaces corn and a protein supplement such as urea or soybean meal. The amount of protein and corn that the WDG displaced in the animal's feed was calculated and then life-cycle production energy for those feed components was assigned. The total credit has a protein and an energy displacement component. The protein credit was calculated by averaging the energy required to produce the amount of urea or soybean meal displaced by WDG in a cattle ration. Many trials have been done estimating the corn displacement ratio for DDGS and wet distillers grains with solubles (WDGS) but little was found for the feeding value of WDG. Trenkle[16] estimates 1 kg of WDG displaces 1 kg of corn on a dry matter basis. We estimate the total co-product credit to be 0.7 MJ/liter (Table 5). This is much lower than previous studies have estimated. Previous studies estimate a DDGS co-product credit of approximately 4.0 MJ/liter.[1,12,14,17]

The WDG credit reported here is lower than previously reported DDGS credits because of the difference in WDG production and DDGS production levels and because of assumptions made regarding feed components displaced in the cattle diet. The WDG production rate of 2.6 kg/bucorn (dm)[8] is much lower than DDGS production of 6.5 kg/bu corn (dm, assuming 15% moisture).[18] The solubles portion of DDGS, accounts for 3.8kg/bu corn (dm).[6-8] In this system the thin stillage is not utilized for animal feed so it is not accounted for in the co-product credit. Previous studies assumed that all the protein in distillers grains is useful to the cattle. However in practice, cattle only require the protein that is supplied by feeding 15% of the cattle dry matter intake with distillers grains. Protein amounts fed above this limit are excreted by the animal as waste.[19] The unutilized protein in the WDG is not accounted for in this credit, making it lower than traditional estimates.

Table 5: WDG Co-product credit*

WDG Inclusion Rate	40%
WDG *(kg/hd)*	3.82
Ave. Protein Credit (MJ/liter)	0.18
Feeding Value WDG (kg/kg_{corn})	1.00
Corn Credit (MJ/liter)	0.59
Total Credit (MJ/liter)	**0.77**

*based on 10.21 $liter_{EtOH}$/Bu_{corn}, Cattle dry matter intake of 8.86 kg/hd/day and 151 days on feed

Land Application Area

The total land application area required to spread the nutrients from the beef-ethanol production system was determined by estimating the levels of phosphorus concentrated in the AD sludge. The AD sludge contains nutrients reclaimed from thin stillage and manure. To estimate the land application area required to spread the nutrients in the sludge, the phosphorus excreted in manure and contained in the thin stillage were used. Fertilization rates are based on phosphate application due to the potential for flash losses of phosphorus from over application of the highly phosphorus concentrated AD sludge.[20] Over application of nitrogen and phosphorus can cause nutrient build-up in field run-off, which contributes to eutrophication. Eutophication in the United States is blamed for decreasing the available oxygen in local streams, resulting in a decline of animal life and for eventually contributing to the steadily expanding hypoxic zone in the Gulf of Mexico.[21]

Although the nutrient content of distillers grains components vary between ethanol plants, literature values show that on average the phosphorus content of thin stillage of 1.23 %.[22-24] Total cattle phosphorus excretion is dependent upon the phosphorus content of the cattle ration (Table 6) which in turn is dependent upon the dry matter intake (DMI). The cattle DMI is assumed to be 8.86 kg/d.[25] The phosphorus levels in the feed components (Table 6) and ASABE standard D384.2, equation 4.3.4, were used to determine the amount of phosphorus excreted in the cattle manure.[11] Cattle feed components (Table 6) were determined using Iowa State University Extension recommendations.[20]

Table 6: Phosphorus content of cattle ration

Feed Component*	% P (dm basis)	% of DMI
Corn[26-28]	0.27	35.0%
Alfalfa/brome hay[27-29]	0.29	12.4%
Corn silage[27,30-31]	0.24	10.1%
WDG [22-24]	0.60	40.0%
Balancer	0	2.0%
Total P (kg/d)	**0.035**	

*average %P values from listed sources

We determined the land area surrounding the plant that would be required to distribute the nutrients concentrated in the AD sludge. The area was converted to a land application radius assuming the sludge would be only be applied to ground planted with corn consisting of 57% of the land area around the plant. Though there are two main crops in the Midwest, soybeans and corn, phosphate fertilizer is generally only applied to land which will be planted in corn. The land application area above is based on US 2007 corn acreage planted as percentage of corn and soybean acreage.[32] A phosphate application rate of 60 lbs/acre based on Iowa State University Extension recommendations of 0.375 lbs P_2O_5/bu_{corn}[33] and an average Iowa corn yield of 160 bu/acre.[34]

Water Usage

Water used in the combined beef-ethanol system is primarily for ethanol production and cattle water consumption. The system boundary only includes the ethanol plant and AD although little water is used in the CAFO compared to the ethanol plant. Cattle consume 43 liters of water/hd/d[35] on average. In the combined system this is expected to be lower due to the water content of the WDG[36] resulting in a cattle water consumption of approximately 2.24 $liters_{water}/liter_{EtOH}$ produced.

It was assumed that significant levels of water would not be required for dilution of the AD influent which is approximately 9.4% solids, based on average thin stillage solids of 7.75%,[24] and manure solids of 14.7%.[11] A total solids content of the influent at 9.4% is within the range of standard AD operating levels which are 2-10% total solids for a complete mixed digester.[37]

The water used in this integrated plant will be significantly higher than water used in a corn dry grind plant which backsets approximately 26% of the thin stillage.[6] In a traditional plant after the backset is removed, the remaining thin stillage is condensed to created Condensed Distillers Solubles (CDS) which is added to wet distillers grains and dried and then commonly used for animal feed. In the condensation process where thin stillage is condensed to condensed distillers solubles (CDS), 66.5% of the water in thin stillage is recovered. Assuming an average thin stillage production rate of 4.97 liters/liter$_{EtOH}$, 3.74 liters$_{H20}$/liter$_{EtOH}$ is recycled from thin stillage in a traditional system (Table 7).

Table 7: Water traditionally recycled from thin stillage (TS), (liter$_{water}$/liter$_{EtOH}$)

TS Backset*	1.29
Water recovered from TS condensation**	2.45
Total Water recovered	3.74

*Based on 26% backset of the thin stillage production , 4.97liter/liter$_{EtOH}$
**Based on 66.5% recovery of TS sent to the condenser after backset. The initial mixture, thin stillage, has a dm content of 7.75%[24], the final mixture, WDG has a dm content of 30%,[24] thus 66.5 % of the water contained in thin stillage is condensed.

In the integrated beef-ethanol system the thin stillage is sent to an anaerobic digester instead of being condensed into CDS. Therefore, water usage in the integrated system will be 3.74 liters/liter$_{EtOH}$ higher than in a traditional ethanol plant.

Results and Discussion

Net Energy of Ethanol Production

The net energy of the integrated system is 13.7 MJ/liter ethanol (Table 8). A representative traditional corn dry grind ethanol system that dries its distillers grains and uses coal or natural gas to power the plant has a net energy value of 4.6 MJ/liter.[1]

Table 8: Net energy of ethanol production for integrated beef-ethanol system

Net Energy Component	(MJ/liter)
Total Fossil Inputs	-7.65
Manure Energy Cost	-0.52
By-product Credit WDG	0.77
Ethanol Energy Content-LHV	21.07
Net Energy	**13.7**

Although this integrated beef-ethanol system has improved energy efficiency over current corn grain ethanol technologies, water usage and land needed for nutrient application present other key issues in the viability of the system.

Land Application Area

A total of 28,000 hectares (not including 57% reduction factor) would be required to spread the nutrients concentrated in the anaerobic digestion sludge on a phosphorus basis (Table 9). The land application area required to spread the nutrients is equivalent to a 12.4 km radius of land surrounding the biofuel production facility (including the 57% reduction factor). To understand the magnitude of this system an average Iowa feedlot with 174 cattle[38] would require only 162 hectares of corn ground or a 0.72 kilometer radius surrounding the feedlot to spread the nutrients on a phosphorus basis.

Table 9: Land application area

Total P in AD sludge (kg/yr)	813,000
P to P2O5 conversion factor	2.29
P2O5 application rate (kg/ha)	60.0
Total area (ha/yr)	28,000

A 12.4 km radius from the plant is a considerable distance to truck wet AD sludge and it is unlikely that the beef-ethanol production facility will have access to that much land directly surrounding the facility. For this reason, it may be necessary to convert the nutrients to a form that is transportable over longer distances. There are various methods that could be employed for nutrient recovery. Options include, ammonia scrubbing of the liquid stream, struvite precipitation through addition of magnesium to recover phosphorus[39], and gasification of anaerobic digestion sludge with subsequent pelletization of the gasifer ash.

Water Usage

The total water usage for the system is 7.1 liters/liter$_{EtOH}$ this is not including the water the feedlot uses (2.2 liters/liter$_{EtOH}$). The water usage at the integrated ethanol plant is higher than that of a traditional corn dry grind ethanol plant because the thin stillage is not recycled. Instead it is sent to an anaerobic digester with cattle manure. Schaefer and Sung[9] recommend reusing the thin stillage stream for process water after anaerobic digestion. This would be possible in the integrated system if the streams are kept separate so that the thin stillage is not contaminated by the manure. If the solids content of the manure digester is too high because the thin stillage which contains higher water content than manure is not present, some of the recovered water may have to be used to dilute this. The 7.1 liters/liter$_{EtOH}$ of water used at the combined beef-ethanol production facility is significantly higher than water usage at a traditional corn dry grind ethanol plant which uses on average 3.45 liters/liter$_{EtOH}$.[2]

Sensitivity Analysis

A sensitivity analysis was performed to determine the most significant parameters affecting the estimates (Table 10). Table 10 shows the factors that most significantly impact the estimates of total water use, net energy and land application area. The parameters are listed with the estimate and variance of the parameter and then its effect on the overall variance of the output. The total water use of the system ranged from 6.3 liters/liter$_{EtOH}$ to 8.7 liters/liter$_{EtOH}$ and depended significantly on the amount of water used in a traditional ethanol plant. The land application area ranged from 24,000 hectares to 33,000 hectares and was most dependent on the phosphate application rate, and the phosphorus content of the distillers grains. The net energy ranged from 11.7 MJ/L to 16.4 MJ/L and was most significantly affected by the volatile solids content and conversion rate in the thin stillage. The water use in an ethanol plant will vary based on the operation and the recycling measures taken. If the thin stillage is recycled after methane production this also have a significant impact. The land application area needed will vary between specific operations and locations. The quality of distillers grains is quite variable across the industry, resulting in variable WDG phosphorus content. Phosphate applications also vary across the Midwest.[4]

Table 10: Sensitivity Analysis*

Parameters	Estimate	Min	Max	Net Energy	Land App. Area	Total Water Use
Thin stillage VS content (kg/L)[9]	0.07	0.05	0.08	56%		
Thin stillage VS to methane ($m^3CH_4/kg_{VS\ added}$)[9]	0.50	0.46	0.62	20%		
Feedstock production[1,12-15]	5.86	5.32	6.72	12%		
Thin stillage production (gpm)[6-8]	247	227	275	8%		
Thermal energy without drying (MJ/L)[4-5]	6.88	6.69	7.06	1%		
Ethanol plant water use (L/LEtOH)[2]	3.45	2.65	4.90			91%
Phosphate application (lbs/acre)[33-34]	60.0	54.0	67.9		63%	
WDG - P content[22-24]	0.60%	0.40%	0.80%		14%	
Thin Stillage P content[22-24]	1.23%	0.71%	1.4%		10%	6%
Cattle DMI (lbs/hd/day)[25]	19.5	16.6	22.3		7%	
Days of plant operation per year (d/yr)[40-43]	344	330	360	1%	3%	2%
Corn P content[26-28]	0.27%	0.23%	0.30%		1%	
Corn sillage P content[27,30,31]	0.24%	0.20%	0.26%			
Feedstock transport[4,12,14]	0.58	0.49	0.64			
Electricity-EtOH production (MJ/L)[2]	0.05	0	0.12			
Ethanol Transport (MJ/L)[1,12-15]	0.39	0.34	0.44			
Methane production from manure[10-11]	0.23	0.21	0.25			
Alfalfa/brome hay P content[27-29]	0.29%	0.24%	0.34%			
WDG co-product credit MJ/liter$_{EtOH}$* *	0.79	0.75	0.83			

*Note: due to rounding errors, sensitivity estimates do not add up to a hundred percent
**based on above mentioned estimates of co-product credits with corn and urea or soybean meal

Conclusions

Co-location and integration of a corn grain dry grind ethanol plant with a cattle CAFO and anaerobic digester produce a higher net energy value than a traditional non-integrated corn grain ethanol plant. However, water usage and nutrient concentration also increase presenting key resources concerns for the system. Multiple possibilities exist to recover nutrients in a transportable form through recycling nutrients back to the field. Closing nutrient cycles by returning nutrients in the system back to the land can enhance the economic and environmental sustainability of biofuel production.

Acknowledgements

The authors would like to acknowledge Albert Bennett for beginning this work during his doctoral preliminary exam at Iowa State University, Dr. Shihwu Sung and Dr. Samir Khanal in the department of Civil, Construction and Environmental Engineering at Iowa State University for providing thin stillage methane production potential data, Dr. Robert Burns and Lara Moody for providing information about anaerobic digestion of cattle manure, Dr. John Lawrence, director of the Iowa Beef Center (IBC) for providing Iowa cattle operations statistics, Dr. Garland Dahlke at IBC for his assistance with protein level determination in cattle diets, and Dr. Allen Trenkle for providing estimates of the feeding value of WDG.

References

1. A.E. Farrell, R.J. Plevin, B.T. Turner, A.D. Jones, M. O'Hare and D.M. Kammen, *Science* 311,506 (2006).
2. M. Wu. Analysis of the Efficiency of the U.S. Ethanol Industry 2007. Center for Transportation Research Argonne National Laboratory Delivered to Renewable Fuels Association on March 27, 2008. Available online: http://www.ethanolrfa.org/objects/documents/1652/2007_analysis_of_the_efficiency_of_the_us_ethanol_industry.pdf. accessed on 22 April 2008.
3. U.S. Grains Council, 2006, Use of DDGS in beef diets, DDGS user handbook. http://www.grains.org/galleries/DDGS%20User%20Handbook/02%20-%20Use%20of%20DDGS%20for%20Beef%20Cattle.pdf.
4. H. Shapouri, D.A. Duffield and M. Wang, 2002. The energy balance of corn ethanol: an update. USDA Agricultural Economic Report Number 814.
5. D.C. Elliott, J.K. Magnuson and C.F. Wend, 3.1.1.2 Feed processing and handling. DL2 Final Report. Pacific National Lab (2006).
6. J.R. Kwiatkowski, A.J. McAloon, F. Taylor and D.B. Johnston, 2006. *Industrial Crops and Products* 23, 288 (2006).
7. M.L. Rasmussen, S.K. Khanal, J.H. van Leeuwen and A.L. Pometto. Bioconversion of thin stillage from corn dry-grind ethanol plants into high-value fungal biomass. ASABE Annual Conference Paper Number: 077030. (2007).
8. M. Haugh, Corn Plus Ethanol. Personal Communication. (March 2008)
9. S.H. Schaefer and S. Sung, *Water Environment Research*, 80, 101 (2008).

10. J.C. Beddoes, K.S. Bracmort, R.T. Burns, and W.F. Lazarus, An analysis of energy production costs from anaerobic digestion systems on U.S. livestock production facilities. USDA, NRCS, Technical Note No.1, October, 2007.
11. ASAE Standard D384.2 Manure production and characteristics, ASABE. St. Joseph, MI (2005).
12. M. Wang, Greet 1.8a – The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. Argonne National Laboratory, Illinois, USA. (http://www.transportation.anl.gov/software/GREET/) (2007).
13. H. Shapouri, J. Duffield, A. McAloon and M. Wang. The 2001 Net Energy Balance of Corn-Ethanol. http://www.ethanolrfa.org/objects/pdf/net_energy_balance_2004.pdf (2004).
14. M.S. Graboski, Fossil energy use in the manufacture of corn ethanol. Prepared for the National Corn Growers Association (2002).
15. M.E.D. deOliveira, M.E. Dias, B.E. Vaughan and E.J. Rykiel. Ethanol as Fuel: Energy, Carbon Dioxide Balances, and Ecological Footprint BioScience *55,7. (2005).*
16. A. Trenkle, Iowa State University, Department of Animal Science. personal communication (August 2007).
17. S. Kim, and B.E. Dale, International Journal of Life Cycle Assessment. 7, 237 (2002).
18. NCGA (National Corn Growers Association). Corn distillers grains: Value-added feed source for beef, dairy beef, dairy, poultry, swine, sheep http://ncga.com/livestock/PDFs/DistillersGrainsBooklet.pdf (2008).

19. G.E. Erickson, T.J. Klopfenstein, D.C. Adams and R.J. Rasby, Utilization of corn co-products in the beef industry: feeding of corn milling co-products to beef cattle. 2nd Ed. University Nebraska Lincoln and Nebraska Corn Board. (2007)
20. R. Wiederholt and B. Johnson, B. Phosphorus behavior in the environment. North Dakota State University publication NM-1298 (2005).
21. N.N. Rabalais, AMBIO 31,102 (2002).
22. G. Lardy, Feeding co-products of the ethanol industry to beef cattle. North Dakata State University Extension publication, AS-1242 (Revised), Available online at: http://www.ag.ndsu.edu/pubs/ansci/beef/as1242w.htm. Accessed on 28 March 2008. (2007).
23. D.D. Loy, and W. Miller, Ethanol co-products for cattle: the process and products. Iowa State University, Iowa Beef Center. IBC-18 (2002).
24. K. Tjardes, and C. Wright, Feeding corn distiller's co-products to beef cattle. South Dakota State University Extension Service. ExEx 2036 (2002).
25. BRaNDS (Beef Ration and Nutritions Decisions Software). Iowa State University Extension. Available online at: http://www.iowabeefcenter.org/content/software_software_brands.html. Accessed 30 March 2008. (2008).
26. M. Raeth-Knight, J. Salfer, and J. Linn. The Ethanol Revolution: How Will We Feed Cows in the Future? University of Minnesota Extension and presented at the University of Minnesota Dairy Days. (2007)
27. C.C. Stallings, Phosphorus content of feeds. Virginia Cooperative Education. Available online at http://www.ext.vt.edu/news/periodicals/dairy/2006-07/phosphorus.html. Accessed 29 March 2008. (2006).

28. A. Viveros, C. Centeno, A. Brenes. R. Canales and A. Lozano. *J. Agric. Food Chem.*, *48,* 4009-4013 (2000).
29. H.B. Sewell. Minerals for beef cattle —supplements. University of Missouri-Columbia Agricultural publication G2081. available at http://www.feedbarnstore.com/animalscience/beef/G02081.pdf. accessed on 22 April 2008. (1993).
30. C.R. Staples. Corn Silage for Dairy Cows. University of Florida IFAS Extension publication DS21. available at http://edis.ifas.ufl.edu/DS082. accessed 22 April 2008. (2003).
31. S. Bosworth. Corn Silage Quality in Vermont. University of Vermont extension publication. Available at: http://www.uvm.edu/pss/vtcrops/articles/CornSilageQuality06Color.pdf. accessed on 22 April 2008. (2006).
32. L. Abendroth and R. Elmore, Crop acreage shift in Iowa and the United States. Department of Agronomy, Iowa State University. Available online at: http://www.ipm.iastate.edu/ipm/icm/2007/4-2/acreage.html. Accessed on 28 March 2008 (2007).
33. ISU. A General Guide for Crop Nutrient and Limestone Recommendations in Iowa. Iowa State University Extension Publication. PM 1688. (2002).
34. D. Smith. Iowa Corn and Soybean County Yields available online: http://www.extension.iastate.edu/AGDM/crops/pdf/a1-14.pdf. Accessed 22 April 2008. (2008).
35. G. Lardy and C. Stoltenow, Livestock and Water. North Dakota State University extension publication AS-954 (1999).

36. IRFA. Distillers Grains Workshop. personal communication, Iowa Renewable Fuels Association, 14 March, 2007. (2007).
37. NRCS. Natural Resources Conservation Service Conservation Practice Standard. Anaerobic Digester – Controlled Temperature. (No.) Code 366. Available online at: http://www.biogas.psu.edu/pdfs/ SafetyPg2&4 NRCSstd366ADControlledTemp05.pdf. Accessed 28 March 2008. (2005).
38. J. Lawrence, personal communication, information from the USDA 2002 Iowa Cattle on Feed, Cattle Sold, 2002 Census of Agriculture (March 2007).
39. A. Miles and T.G. Ellis. Water Science and Technology. 43,259-266 (2001).
40. C. Hurt. Potential Implications of Indiana’s booming ethanol industry. Purdue University. Available at: http://www.purdue.edu/dp/energy/centers/bioenergy/presentations/EthanolInd%20-%20C.%20Hurt%20File.pdf. Accessed on 22 April 2008. (2006).
41. M. Bryan. Iowa Ethanol Plant Pre-Feasibility Study. Prepared for Iowa Ethanol sub committee. Available at: http://www.ethanolrfa.org/objects/pdf/ethanol_ resource_manual.pdf. accessed on 22 April 2008. (2000).
42. Booth Associates Pty Ltd. Four Arrows Rural group. Introductory Environmental report for a proposed integrated ethanol plant and intensive dairy. Available at: http://www.planning.nsw.gov.au/asp/pdf/06_0020_pre-planning_focus_meeting_rpt.pdf. Accessed on 22 April 2008. (2005).
43. T. Crooks. Farmer ethanol in a "flat world" - how information technology is changing the nature of fuel ethanol operations. Presented at the conference: Energy from Agriculture: New Technologies, Innovative Programs & Success Stories, St. Louis MI. December 14-15 (2005).

CHAPTER 5

General Conclusions

Capturing nutrients in integrated biofuel production systems and recycling them back to crop land provides opportunities to enhance the economic and environmental sustainability of the systems. Land applying biomass ash from thermochemical conversion of biomass and capturing nutrients in beef-ethanol production systems are two ways of recycling nutrients concentrated from biofuel production. Allocation is a useful tool for distributing environmental and energy burdens between biofuels and co-products containing useful nutrients.

Before biomass ash can be land applied effectively, it must be transformed due to its light and powdery texture. Pelleting ash may provide ease of transport and application. Conclusions from the preliminary ash pelleting trials reported in this thesis show that binder and binder type have a significant effect on the physical and chemical properties of the pellets. Moisture content has a significant effect on the durability and degradability of the pellets. Condensed distillers solubles, a byproduct from the ethanol industry did not make an effective binder due to its extremely low durability. The durability and degradability of the ash pellets have opposing trends. Overall the degradability and durability of the pellets with lower inclusion levels of DDGS and Bone meal were not statistically different than higher levels. Assuming 15% binder inclusion levels and that the total P & K present in the pellets is completely available, ash pellets cost 86% less to produce than the current cost of the commercial fertilizer it would replace. The ash pellets contained significant levels of nutrients; however, field trials need to be performed to determine the bio-available nutrients in the pellets.

Nutrients in dry grind ethanol production concentrate in distillers grains (DG) commonly used for animal feed. Allocation was used to estimate an energy co-product credit for dry grind ethanol production. Ethanol co-product credits are typically calculated assuming fixed feed component displacement ratios and inclusion rates. In practice DG inclusion rates vary in cattle diets. The co-product credits reported in this thesis are lower than previous estimates and vary with the feed components the DG displaced and the inclusion level of DG in cattle diets. The ethanol co-product credit for corn dry grind ethanol production was estimated to range from 2.2 MJ/L to 4.3MJ/L depending on the type of DG added to the animal diet, the type of feed component displaced and the distillers grains inclusion rates in the diet. Corresponding net energy calculations for a typical dry grind ethanol system range from 2.7 MJ/L to 4.8 MJ/L.

In an integrated Beef-Ethanol production facility with waste digesters, significant levels of nutrients concentrate in anaerobic digestion sludge and could be captured for fertilizer. Integration of beef and ethanol production systems produces a higher ethanol net energy than in current corn dry grind ethanol production but spatially increases water consumption and nutrient concentration compared to stand alone beef and ethanol production facilities. The net energy of the integrated system is 13.7 MJ/L compared to 4.6 MJ/L for a non-integrated corn dry grind ethanol plant. The integrated system requires twenty-eight thousand hectares for spreading the reclaimed nutrients from the manure and thin stillage and consumes 7.1 L_{water}/L_{EtOH}, compared to 4 L/L_{EtOH} in a conventional system. Nutrients can be extracted at several points in the system and can potentially be returned to crop fields as soil amendments or fertilizers. Utilizing the nutrients from this integrated biofuel production system to close nutrient cycles, mimicking natural ecosystems, will increase the overall system sustainability.

Future Work

To guide decision making about the commercial viability of producing ash pellets, pelletizing trials and technoeconomic analyses comparing different pelletizing technologies should be performed. Due to variation in the physical and chemical characteristics of ash, pelleting trials, greenhouse studies and field trials are needed for each ash stream to evaluate its use as a potential fertilizer. Estimating the net energy of ash recovery and pelleting is needed to determine if ash recovery is energetically desirable.

When performing co-product allocation it is important to consider that the credit will vary depending on the co-products use. Many co-products have multiple uses, for example thin stillage which can be anaerobically digested to create biogas, condensed and combusted for energy, condensed and used in animal feed rations in the form of CDS or added to wet grain and in the form of DDGS. As the ethanol industry matures, the number and variety of ethanol co-products will continue to increase. The appropriate co-product credit and resulting system net energy estimate will vary with the suite of co-products produced and their uses.

Additional ash pellet trials

Table 1: Nutrient, degradability and liming equivalence analysis of additional pellet trials*

Ash/char origin	Binder	BL	MC	pH	Total P (%)	Total K (%)	Water P (ppm)	Water K (%)	Water N (ppm)	Total C (%)	Total N (%)	4-mesh	8-mesh	50-mesh
char – gasified wood	DDGS			10.35	0.5%	1.0%	289	0.13%	10	**40.2%**	2.4%	92.4%	92.4%	31.2%
char-gasified stover or wood	DDGS	20%		12.58	1.3%	3.0%	79	0.53%	25	**36.3%**	1.2%	8.9%	8.9%	3.6%
char-gasified stover or wood	DDGS	50%		11.33	1.6%	4.2%	417	1.01%	49	**40.6%**	2.5%	68.9%	68.9%	18.9%
char – gasified stover	DDGS			8.53	0.4%	1.0%	711	0.56%	33	**37.7%**	2.5%	88.7%	88.7%	21.6%
char – gasified stover	None	0%	30%	7.35	0.2%	0.8%	293	0.24%	6	**24.9%**	0.80%	100%	100%	91%
ash-cumbusted CDS	Bone meal	16%	30%	10.94	**7.1%**	**8.3%**	71	4.67%	67	5.6%	0.52%	66.6%	66.6%	44.4%
ash-cumbusted CDS	Bone meal	20%	20%	11.67	**7.4%**	**8.7%**	138	6.91%	42	6.2%	0.62%	59.9%	59.9%	54.2%
ash-cumbusted CDS	Bone meal	44%	30%	10.94	**8.8%**	**6.1%**	153	4.69%	28	11.4%	1.4%	98.5%	98.5%	68.3%
ash-cumbusted CDS	DDGS	44%	20%	12.00	**4.3%**	**6.4%**	811	4.78%	45	21.8%	2.0%	97.6%	97.6%	43%
ash-cumbusted CDS	DDGS	20%	20%	11.60	**4.8%**	**10.8%**	345	6.11%	21	11.6%	0.95%	44.4%	44.4%	24.4%

*Note the gasifier char is rich in carbon but low in P and K and the combusted ash is low in carbon but rich in P & K

Biographical Sketch

Katherine Adell Edwards was born August 1, 1986 in Iowa City, Iowa. She received the Associate of Science from Scottsdale Community College in 2003, the Bachelor of Science in Agricultural Engineering from Iowa State University in 2007 and the Master of Science in Agricultural Engineering and Biorenewable Resources and Technology from Iowa State University in 2008. She was awarded the Iowa State University College of Engineering Deans Fellowship. She has served as an undergraduate and graduate Research Assistant in the Department of Agricultural Engineering at Iowa State University, and as an intern at Caterpillar and in Cambridge, England.