Rosentrater, K. A. 2005. Expanding the role of systems modeling: considering byproduct generation from biofuel production. *Ecology and Society* **11**(1): r2. [online] URL: http://www.ecologyandsociety.org/vol11/iss1/resp2/

Response to Chan *et al*. 2004. "The Role of Systems Modeling for Sustainable Development Policy Analysis: the Case of Bio-Ethanol"

Expanding the Role of Systems Modeling: Considering Byproduct Generation from Biofuel Production

Kurt A. Rosentrater[1]

ABSTRACT. The bioethanol industry has been experiencing rapid growth over the past several years, and is expected to continue to increase production for the foreseeable future. A vital component to the success of this industry is the sales and marketing of processing residues, which are primarily sold as dried distillers grains with solubles (DDGS). Systems modeling, a technique that has been used to predict future demand for bioethanol, can also be used to determine potential byproduct generation rates. This paper discusses the development of one such model, and presents predicted generation of DDGS as well as carbon dioxide emissions from this industry through 2100. These simulation results underscore the growing need to actively pursue research focused on value-added alternatives for the use of bioethanol byproduct streams.

Key Words: *bioethanol; biofuels; byproducts; carbon dioxide emissions; distillers grains; dynamic systems modeling; policy analysis; residue generation*

INTRODUCTION

With growing population, industrialization, and energy consumption, coupled with an increasing reliance on fossil fuels, the energy security needs of North America continue to escalate. Biofuels, renewable sources of energy, can help meet these increasing needs, and are produced from biomass sources including corn stover, residue straw, perennial grasses, legumes, and other agricultural and biological materials. At the moment, the most heavily used is corn. Fermentation of corn is readily accomplished at a relatively low cost vis-à-vis other biomass sources. However, in the coming years, the conversion of other lignocellulosic materials is expected to become cost competitive due to rapid technological advances (DePardo 2000).

Concern over resource inputs/outputs, economics, and impact of manufacturing and the use of bioethanol has led to many life cycle assessment studies (LCA). In addition to Chan et al. (2004), prominent studies include Andress (2002), Kaltschmitt et al. (1997), Kim and Dale (2002, 2004), Lynd and Wang (2004), Shapouri et al. (1995, 2002, 2003*a*,*b*), and Sheehan et al. (2002, 2004). Each manufacturing plant needs to contribute to the mission of sustainability in order for the entire system to succeed. A key element to this approach is to examine waste and byproduct streams (Rosentrater 2004). Modeling and simulation provides a tool for such analysis.

The primary objectives of this study are two-fold: 1) to further the discussion regarding the use of computer simulation to provide insights into bioethanol manufacturing, and 2) to expand the discussion to include processing residues. Based on Chan et al. (2004), a computer model was constructed to determine the quantity of byproducts resulting from bioethanol manufacture. This paper, therefore, raises the issue of the use and/or disposal of byproducts generated as this industry expands.

[1]U.S. Department of Agriculture, Agricultural Research Service

Fig. 1. Nonfermentable residues–dried distillers grains with solubles (DDGS).

CORN ETHANOL: A CASE STUDY IN BIOFUEL MANUFACTURING

Although the bioethanol industry is poised to produce substantial quantities of biofuel during the next century, corn grain is currently the only biological material that can be economically converted into ethanol on an industrial scale. Thus, it is useful to examine this segment of the industry to establish a baseline for the consideration of bioethanol production from other potentially viable lignocellulosic materials.

Briefly, bioethanol manufacturing from corn grain results in three products: bioethanol, the primary end product; residual nonfermentable corn kernel components, which are typically marketed as "dried distillers grains with solubles," known as "DDGS" (Fig. 1); and carbon dioxide (Fig. 2). Anecdotally, the rule of thumb commonly used in industry states that for 1 kg of corn processed, approximately 1/3 kg of each of the constituent product streams will be produced. The production process (Fig. 3) consists of several key steps, including grinding, cooking, liquefying, fermenting, and distilling the corn grain. Indepth information on this process, which is beyond the scope of this paper, can be found in Dien et al. (2003), Jaques et al. (2003), Tibelius (1996), and Weigel et al. (2005). Carbon dioxide results from the fermentation stage during starch consumption and metabolic conversion by yeast. This byproduct stream can be sold to specific compressed gas markets. Often, however, it is released to the atmosphere, because location or logistics prevent economic marketing. Distillers grains, on the other hand, are removed from the distillation stage, dried to ensure a substantial shelf life, and then sold to local livestock producers or shipped via truck or rail for use in distant livestock feed rations. Their sale contributes substantially to the economic viability of bioethanol manufacturing, and is vital to each plant's operations. The quantity of processing residues that will be produced will substantially influence the future of the industry. Predictions of these can be accomplished via computer modeling and simulation.

Fig. 2. Steam and carbon dioxide discharge from a typical corn-to-bioethanol manufacturing plant.

Simulating byproduct generation

To predict the quantity of byproducts that may be produced during the next century by bioethanol manufacturing operations, a computer model was constructed using spreadsheet software. Several conversion factors were necessary to consider and incorporate, including: (1) Corn-to-bioethanol conversion (CEC): 2.58 kg corn/L bioethanol (Kim and Dale 2002); (2) Corn-to-byproducts conversion: 25.4 kg of corn typically produces approximately 7.98 kg of bioethanol, 7.71 kg of DDGS, and 8.35 kg of carbon dioxide (Kelsall and Lyons 2003). This equates to a corn-to-distillers grains conversion (CDGC) of 3.29 kg corn/kg DDGS, and a corn-to-carbon dioxide conversion (CCDC) of 3.04 kg corn/kg CO_2; and (3) Energy density (ED) of bioethanol: 2.12×10^7 J/L (Sheehan et al. 2004).

To model the quantity of byproducts that may be produced during this time frame, i.e., 100 yr, several steps were involved. Briefly, key calculations included the rate of energy use (EU_1; J/yr): information was based on predictions by Chan et al. (2004), Scenarios B and C.

Fig. 3. Process flow diagram of corn-to-bioethanol manufacturing process.

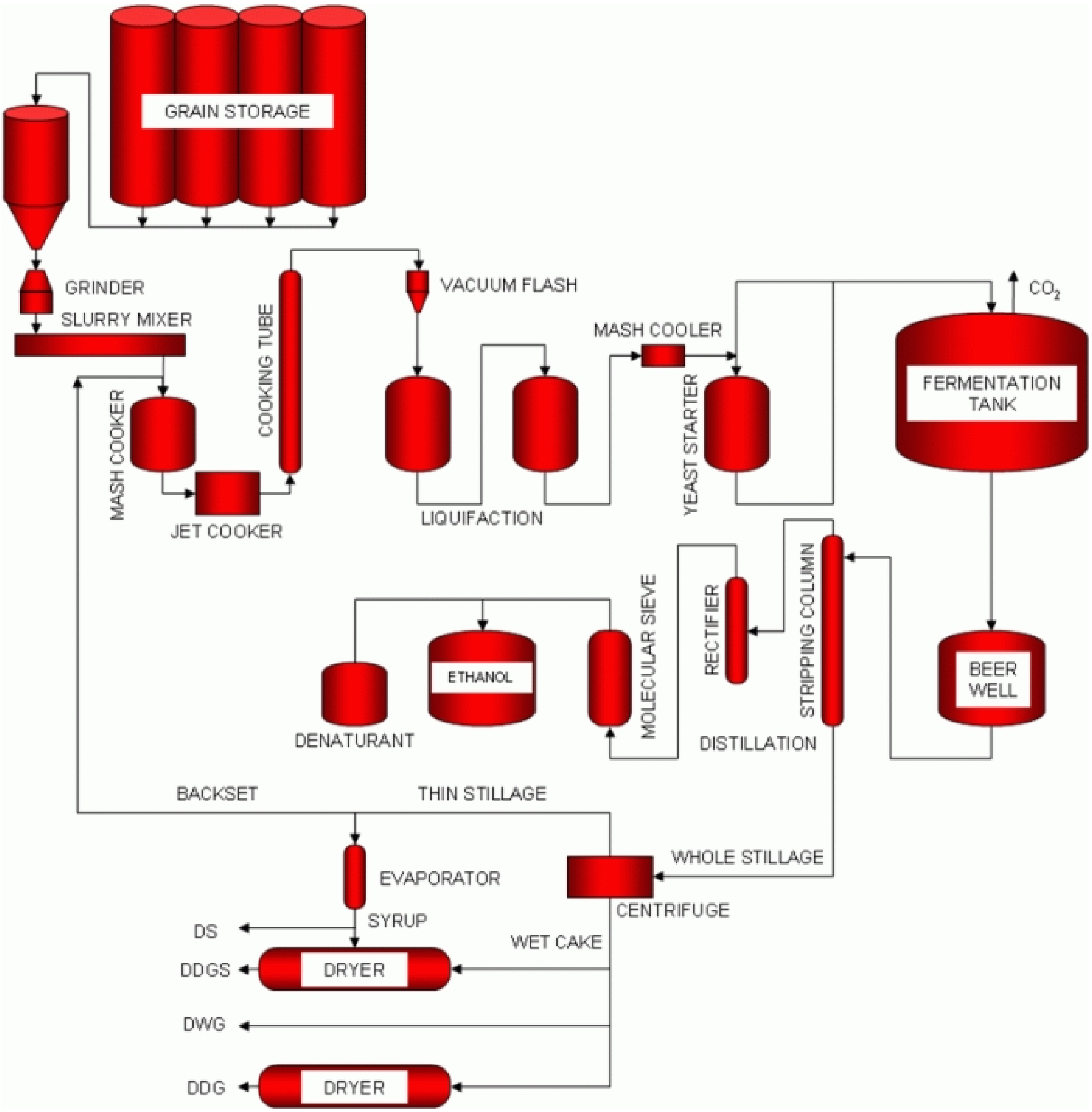
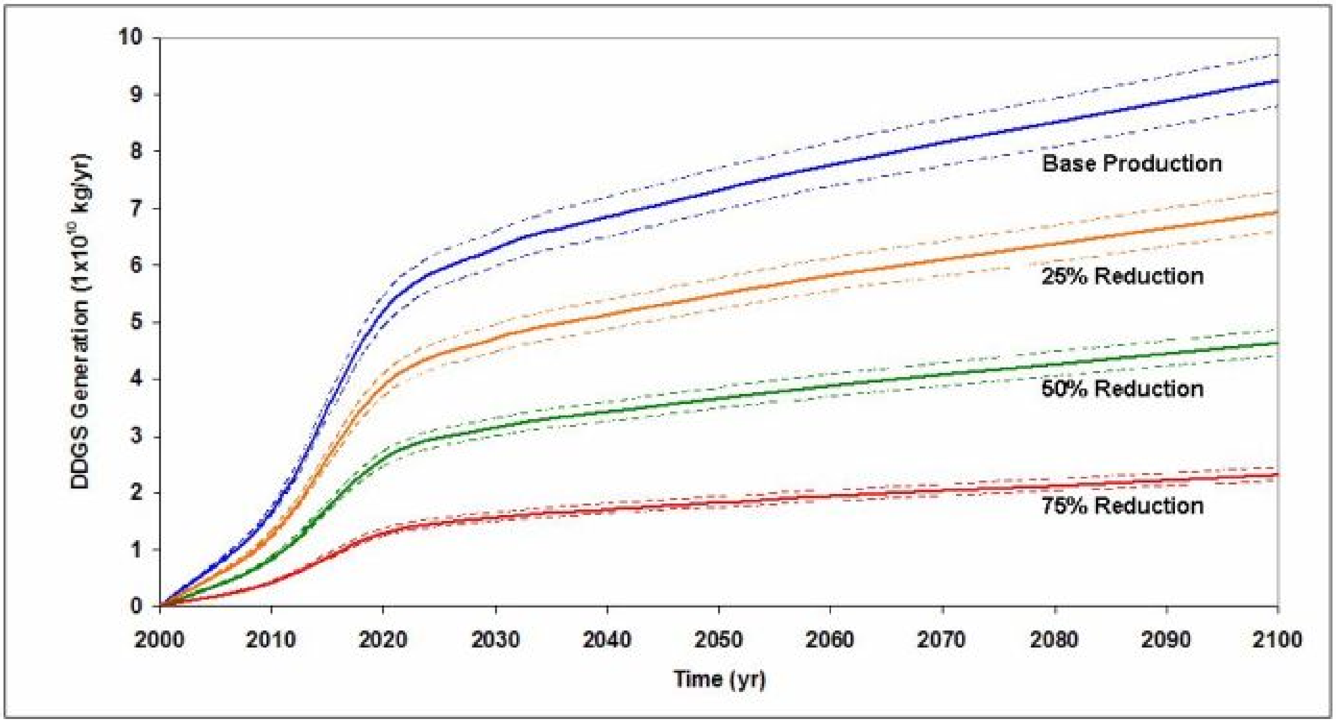


Fig. 4. Projected generation of DDGS under Scenario B.



Rate of ethanol use (EU_2; L/yr):

$$EU_2 = \frac{EU_1}{ED} \quad (1)$$

Rate of corn use (CUR; kg/yr):

$$CUR = EU_2 \cdot CEC \quad (2)$$

Dried distillers grains with solubles generation rate (DDGS; kg/yr):

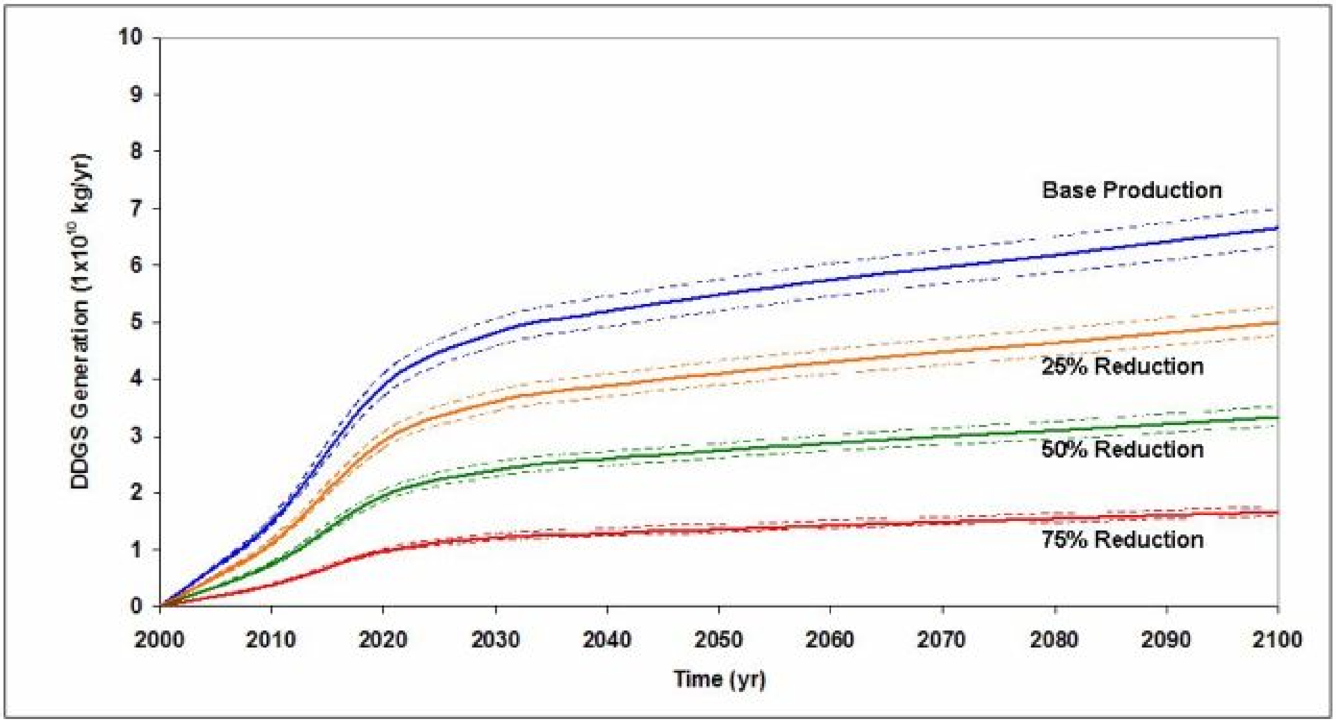
$$DDGS = \frac{CUR}{CDGC} \quad (3)$$

Carbon dioxide generation rate (CD; kg/yr):

$$CD = \frac{CUR}{CCDC} \quad (4)$$

After programming, simulations were constructed based on energy use Scenarios B and C. However, the model can be used to simulate other use scenarios as well.

Fig. 5. Projected generation of dried distillers grains with solubles (DDGS) under Scenario C.



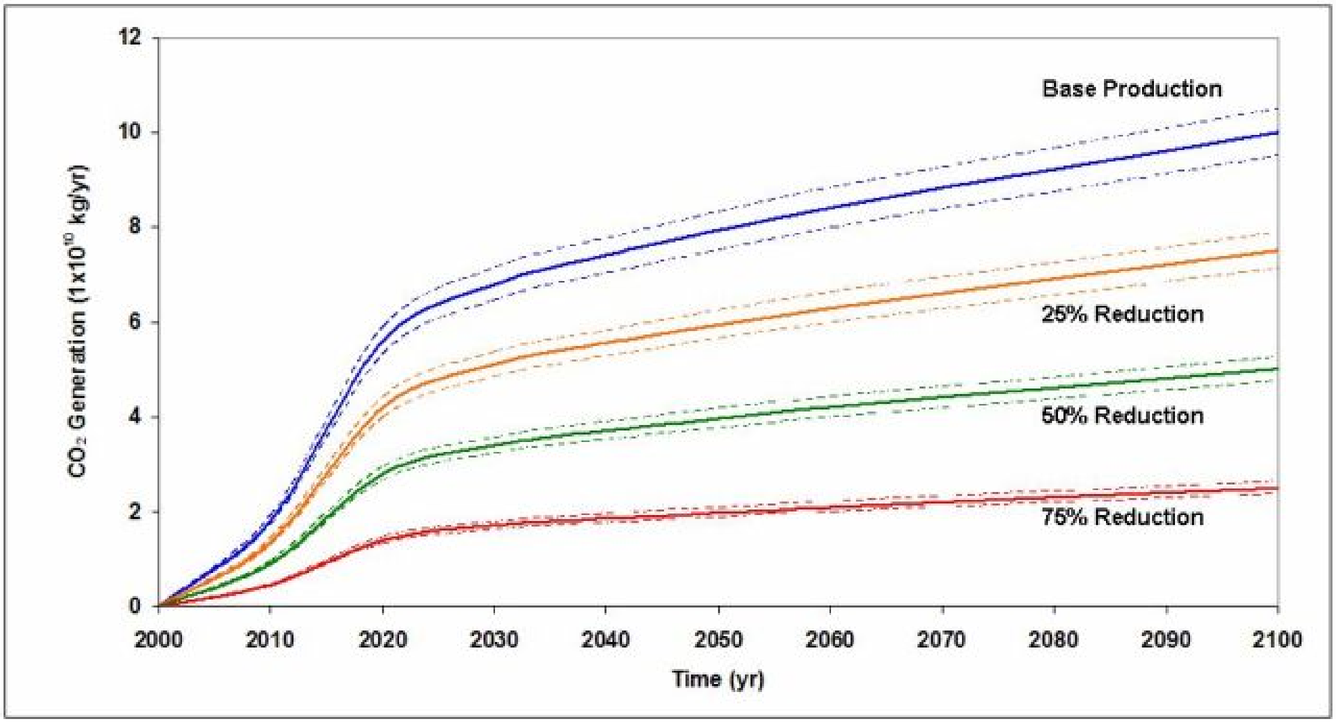
Simulation results

When constructing simulations, it is crucial to account for potential variations in numerical quantities and conversion factors, because these impact resulting calculated values. Literature reports a broad range of corn-to-distillers grains conversion, i.e., DDGS, rates from 0.282 to 0.323 kg DDGS/kg corn, as well as corn-to-carbon dioxide conversion, i.e., CCDC rates from 0.287 to 0.329 kg CO_2/kg corn (Dien et al. 2003, Kim and Dale 2002, Lyons 2003, Shapouri et al. 1995, Tibelius 1996). These variations substantially affect the quantity of predicted byproducts that are determined by the computer model. Moreover, at individual manufacturing plants, variations in raw material inputs, equipment used, and operational procedures result in conversion rates that do not match values found in literature, but instead vary stochastically over both time and location. However, much of this information is proprietary and is not available in the literature. The computer model had to accommodate these variations, which thus led to differences in the calculated generation rates of the byproduct streams. Potential variations can most simply be accounted for by providing a range of potential conversion factors in the programming itself. In this study, ± 5% of the calculated conversion values were used to achieve this range.

Figure 4 predicts DDGS produced (± 5%) according to the quantity of manufactured bioethanol if Scenario B is realized; Fig. 5 depicts results for Scenario C. Figure 6 illustrates the carbon dioxide generated (± 5%) if Scenario B is realized; Fig. 7 depicts results for Scenario C. Not surprisingly, production rates of the byproducts increase in parallel with the quantity of bioethanol, as predicted by Chan et al. (2004). Most notably, the construction of this model has allowed specific quantities of byproducts to be predicted over time.

Recently, research has begun to address process modifications to reduce the amount of manufacturing byproducts. These include Barnes (2003), Johnston

Fig. 6. Projected generation of CO_2 under Scenario B.



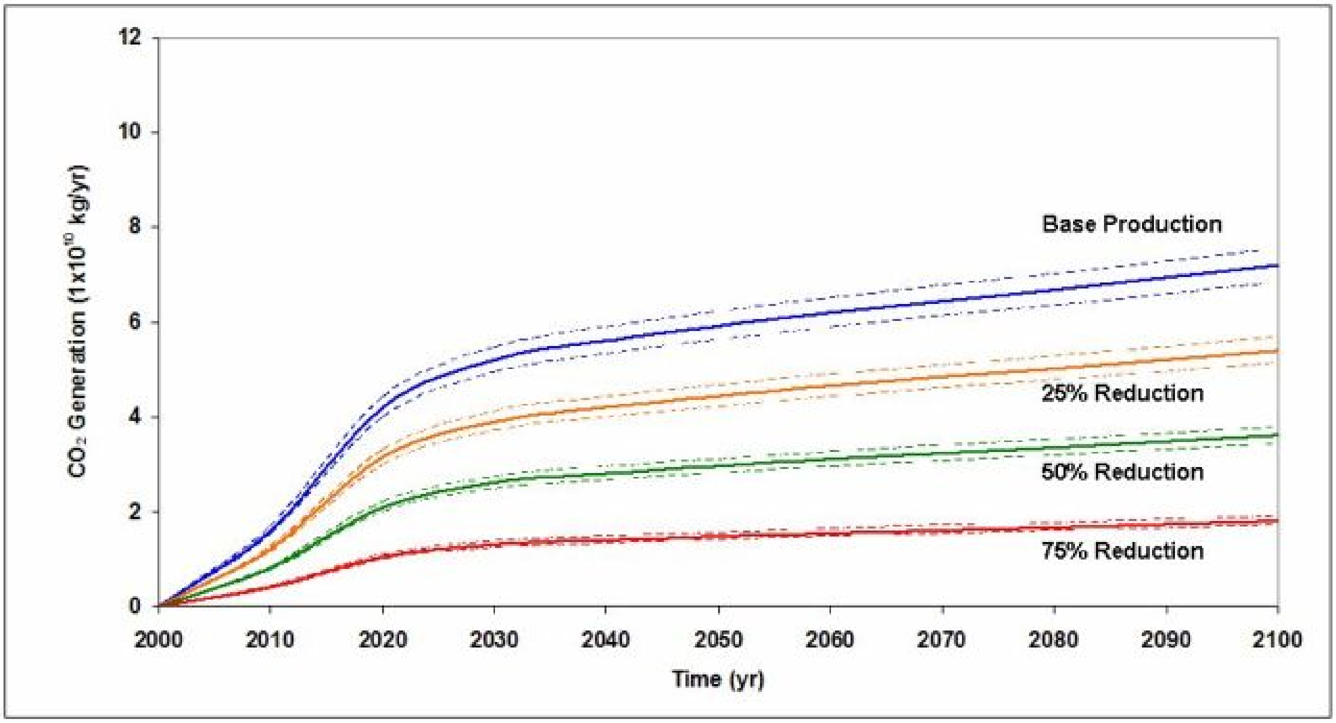
and Singh (2003), Murthy et al. (2004), Naidu and Singh (2003), Singh et al. (2001*b*), Singh et al. (2003), Singh et al. (2004), and Wahjudi et al. (2000). Figures 4 through 7, therefore, also illustrate production rates if these newer technologies can achieve 25, 50, and 75% reductions. If these modifications can be commercially implemented in production facilities, drastic reductions in generated byproducts could be realized. Thus, the success or failure of technological innovation has the potential for profound ecological ramifications as this industry continues to grow.

Regardless of potential new technologies, the overarching issue brought to light from these simulation results is the substantial increase in both distillers grains and carbon dioxide during the next century. The increased supply of distillers grains will affect the potential sales price vis-à-vis feed demand, whereas allowable carbon dioxide generation will be affected by greenhouse gas emission constraints. Both of these issues could severely affect the production economics of the industry in the near future. If estimates of future bioethanol production hold true, the current unidirectional approach may not be sustainable; thus, alternative avenues of use are necessary.

BYPRODUCT USE POSSIBILITIES

Currently, the bioethanol industry's only outlet for the nonfermentable residues from the manufacturing process is livestock feeds. This approach is well established, but must be augmented if it is to retain its high-value returns because the generated quantities increase over time. Other novel uses such as human foods and industrial products should also be pursued.

Fig. 7. Projected generation of CO_2 under Scenario C.



Feed uses

Feeding dried distillers grains with solubles (DDGS) to animals is a viable method for the use of nonfermentable residues, because they contain high nutrient levels. Over the years, numerous studies have been conducted to optimize their use in livestock feed rations. Aines et al. (1986) and UM (2004) provide comprehensive reviews. Even so, much work remains to improve and maximize the use of these residues in animal feeds. Priorities should include:

1. Densification via pelleting or cubing to improve bulk density, storability, transportation, and delivery;
2. Extrusion processing to produce value-added feed products;
3. Storability, shelf life, and preservation assessment; and
4. Feeding trials and acceptability testing.

Food uses

Studies have also examined the possibility of using these streams in human food products. Some of the most recent include Abbott et al. (1991), Bookwalter et al. (1984), Brochetti et al. (1991), Kim et al. (1989), Maga and van Everen (1989), Rasco et al. (1990), van Everen et al. (1992), and Wall et al. (1984). To date, however, no commercial food products incorporate DDGS. In order for viable products to be successfully manufactured, additional research is needed. Studies essential to this effort include: (1) Analysis of current DDGS streams for food-grade applicability, especially nutritional contents and chemical levels, including vitamins, minerals, nucleic acids, pigments, heavy metals, and toxic compounds; and (2) Methods for processing DDGS into food grade ingredients, including:

1. Pretreatments such as separation and concentration of proteins, fibers, lipids, or other compounds;
2. Washing, cleaning, and quality upgrading;
3. Bleaching, deodorizing, and sterilizing;
4. Milling into corn flour;
5. Development of specific food products such as bakery goods, noodles, pastas, or other low carbohydrate, high protein, high fiber foods;
6. Storability, shelf life, and preservation assessment; and
7. Sensory analysis and acceptability testing.

Industrial uses

Beyond these, little work to develop other value-added applications has been undertaken. Initial trials have been conducted investigating soil amendments and fertilizers (Erdem and Ok 2002, Ramana et al. 2002*a*,*b*), plastic composites (Julson et al. 2004), and extracting industrial chemicals (Kwiatkowski and Cheryan 2002, Singh and Cheryah 1998, Singh et al. 2001*a*, 2002). Other potential avenues do exist, and should be investigated, including:

1. Fractionation into component-rich, i.e., protein, fiber, oil, streams;
2. Hydrolysis to release additional sugars for fermentation;
3. Energy generation, including pyrolysis and gasification;
4. Biodegradable plastic composites; and
5. Wood composites.

Carbon Dioxide Emissions

Very little work has investigated the capture and use of carbon dioxide (Ginger 2004, Marland and Turhollow 1991). As demand for bioethanol increases, and more manufacturing plants are constructed and expanded, it will become essential to consider this issue, especially because the issue of greenhouse gas emissions continues to gain importance in environmental policies.

CONCLUSIONS

The bioethanol industry is poised to significantly contribute to meeting rising energy demands in coming years. Because this industry is not yet fully mature, questions have arisen regarding the nature of the industry itself. One concern is the quantity of byproducts that will be generated; thus, considering how these residues will ultimately be used is vital. Simulation modeling provides a tool that can be used to predict residue generation rates, and provide a baseline that can be used for discussions regarding use, as well as policy analyses for the bioethanol industry as a whole. Examining potential generation rates for the coming century underscores the pressing need for research and development into value-added uses for these materials if, given the current level of technology, the bioethanol industry is to remain cost competitive.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol11/iss1/resp2/responses/

Acknowledgments:

The author would like to acknowledge the helpful comments by the reviewers and editors.

LITERATURE CITED

Abbott, J., J. O'Palka, and C. F. McGuire. 1991. Dried distillers' grains with solubles: particle size effects on volume and acceptability of baked products. *Journal of Food Science* **56**(5):1323-1326.

Aines, G., T. Klopfenstein, and R. Stock. 1986. *Distillers Grains, MP51.* University of Nebraska Cooperative Extension. Available online at: http://ianrpubs.unl.edu/fieldcrops/mp51.htm.

Andress, D. 2002. *Ethanol energy balances.* Subcontract 4000006704 Report. Office of Biomass Programs, U.S. Department of Energy, Washington, D.C., USA.

Barnes, W. 2003. Retrofitting an existing dry grind ethanol plant to expand coproduct values. Page 71 *in* M. Tumbleson, V. Singh, and K. Rausch, editors. *The Third International Starch Technology Conference–Coproducts Program Proceedings* (Urbana, 2003). University of Illinois, Urbana, Illinois, USA.

Bookwalter, G. N., K. Warner, J. S. Wall, and Y. V. Wu. 1984. Corn distillers' grains and other by-products of alcohol production in blended foods. II. Sensory, stability, and processing studies. *Cereal Chemistry* **61**(6):509-513.

Brochetti, D., M. P. Penfield, and M. F. Heim-Edelman. 1991. Yeast bread containing distillers' dried grain: dough development and bread quality. *Journal of Food Quality* **14**:331-344.

Chan, A. W., R. Hoffman, and B. McInnis. 2004. The role of systems modeling for sustainable development policy analysis: the case of bio-ethanol. *Ecology and Society* **9**(2):1-17.

Dien, B. S., R. J. Bothast, N. N. Nichols, and M. A. Cotta. 2003. The U.S. corn ethanol industry: an overview of current technology and future prospects. Pages 10-21 *in* M. Tumbleson, V. Singh, and K. Rausch, editors. *The Third International Starch Technology Conference–Coproducts Program Proceedings* (Urbana, 2003). University of Illinois, Urbana, Illinois, USA.

DiPardo, J. 2000. *Outlook for biomass ethanol production and demand.* U.S. Department of Energy, Energy Information Agency. Washington, D.C., USA. Available online at: www.eia.doe.gov/oiaf/analysispaper/biomass.html"

Erdem, N. and S. S. Ok. 2002. Effect of brewery sludge amendments on some chemical properties of acid soil in pot experiments. *Bioresource Technology* **84**:271-273.

Ginger, B. 2004. Pollution control help for ethanol production. *Pollution Engineering* **37**(1):12-14.

Jaques, K. A., T. P. Lyons, and D. R. Kelsall. 2003. *The Alcohol Textbook.* Nottingham University Press, Nottingham, UK.

Johnston, D. B. and V. Singh. 2003. Product yield comparison using enzymatic milling with reduced levels of bromelain and varying levels of sulfur dioxide. Page 128 *in* M. Tumbleson, V. Singh, and K. Rausch, editors. *The Third International Starch Technology Conference–Coproducts Program Proceedings* (Urbana, 2003). University of Illinois, Urbana, Illinois, USA.

Julson, J. L., G. Subbarao, D. D. Stokke, H. H. Gieselman, and K. Muthukumarappan. 2004. Mechanical properties of biorenewable fiber/plastic composites. *Journal of Applied Polymer Science* **93**:2484-2493.

Kaltschmitt, M., G. A. Reinhardt, and T. Stelzer. 1997. Life cycle analysis of biofuels under different environmental aspects. *Biomass and Bioenergy* **12**(2):121-134.

Kelsall, D. R. and T. P. Lyons. 2003. Practical management of yeast: conversion of sugars to ethanol. Pages 121-133 *in* K. A. Jaques, T. P. Lyons, and D. R. Kelsall, editors. *The Alcohol Textbook.* Nottingham University Press, Nottingham, UK.

Kim, C. H., J. A. Maga, and J. T. Martin. 1989. Properties of extruded dried distiller grains (DDG) and flour blends. *Journal of Food Processing and Preservation* **13**:219-231.

Kim, S. and B. E. Dale. 2002. Allocation procedure in ethanol production system from corn grain. I. System expansion. *International Journal of Life Cycle Assessment* **7**(4):237-243.

Kim, S. and B. E. Dale. 2004. Cumulative energy and global warming impacts from the production of biomass for biobased products. *Journal of Industrial Ecology* **7**(3-4):147-162.

Kwiatkowski, J. and M. Cheryan. 2002. *Ethanol extraction of oil from dry-milled corn: process optimization and rheological properties of the* *extract.* American Society of Agricultural Engineers (ASAE) Meeting Paper Number 026144. St. Joseph, Missouri, USA.

Lynd, L. R. and M. Q. Wang. 2004. A product-nonspecific framework for evaluating the potential of biomass-based products to displace fossil fuels. *Journal of Industrial Ecology* **7**(3-4):17-32.

Lyons, T. P. 2003. Ethanol around the world: rapid growth in policies, technology, and production. Pages 1-7 *in* K. A. Jaques, T. P. Lyons, and D. R. Kelsall, editors. *The Alcohol Textbook.* Nottingham University Press, Nottingham, UK.

Maga, J. A. and K. E. van Everen. 1989. Chemical and sensory properties of whole wheat pasta products supplemented with wheat-derived dried distillers grain (DDG). *Journal of Food Processing and Preservation* **13**:71-78.

Marland, G. and A. F. Turhollow. 1991. CO_2 emissions from the production and combustion of fuel ethanol from corn. *Energy* **16**(11-12):1307-1316.

Murthy, G. S., K. D. Rausch, D. B. Johnston, M. E. Tumbleson, and V. Singh. 2004. *Effect of corn endosperm hardness on different stages of dry grind corn process.* American Society of Agricultural Engineers (ASAE) Meeting Paper Number 026144. St. Joseph, Missouri, USA.

Naidu, K. and V. Singh. 2003. *Effect of corn flour particle size on ethanol yield and soluble solids in thin stillage in a dry grind process.* American Society of Agricultural Engineers (ASAE) Meeting Paper Number 036067. St. Joseph, Missouri, USA.

Ramana, S., A. K. Biswas, S. Kundu, J. K. Saha, and R. B. R. Yadava. 2002*a*. Effect of distiller effluent on seed germination in some vegetable crops. *Bioresource Technology* **82**:273-275.

Ramana, S., A. K. Biswas, and A. B. Singh. 2002*b*. Effect of distillery effluents on some physiological aspects in maize. *Bioresource Technology* **84**:295-297.

Rasco, B. A., G. Rubenthaler, M. Borhan, and F. M. Dong. 1990. Baking properties of bread and cookies incorporating distillers' or brewer's grain from wheat or barley. *Journal of Food Science* **55**(2):424-429.

Rosentrater, K. A. 2004. Strategic methodology for advancing food manufacturing waste management paradigms. Pages 274-285 *in* S. M. Gupta, editor. *Environmentally conscious manufacturing IV, Proceedings of the Society of Photo-Optical Intrumentation Engineers* (Bellingham, 2004). Bellingham, Washington, USA.

Shapouri, H., J. A. Duffield, and M. S. Graboski. 1995. *Estimating the net energy balance of corn ethanol.* U.S. Forest Service, Economic Research Service, Office of Energy and New Uses. Report Number 721. Washington, D.C, USA.

Shapouri, H., J. A. Duffield, and M. Wang. 2002. *The energy balance of corn ethanol: an update.* U. S. Forest Service Research Paper Number 813. Washington, D.C., USA.

Shapouri, H., J. A. Duffield, and M. Wang. 2003*a*. The energy balance of corn ethanol: an update. Page 73 *in* M. Tumbleson, V. Singh, and K. Rausch, editors. *The Third International Starch Technology Conference–Coproducts Program Proceedings* (Urbana, 2003). University of Illinois, Urbana, Illinois, USA.

Shapouri, H., J. A. Duffield, and M. Wang. 2003*b*. The energy balance of corn ethanol revisited. *Transactions of the American Society of Agricultural Engineers (ASAE)* **46**(4):959-968.

Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelson. 2004. Energy and environmental aspects of using corn stover for fuel ethanol. *Journal of Industrial Ecology* **7**(3-4):117-146.

Sheehan, J., A. Aden, C. Riley, K. Paustian, K. Killian, J. Brenner, D. Lightle, R. Nelson, M. Walsh, and J. Cushman. 2002. *Is ethanol from corn stover sustainable?* National Renewable Energy Laboratory, Golden, Colorado, USA.

Singh, N. and M. Cheryan. 1998. Extraction of oil from corn distillers dried grains with solubles. *Transactions of the American Society of Agricultural Engineers (ASAE)* **41**(6):1775-1777.

Singh, V., B. S. Dien, R. J. Bothast, R. A. Moreau, D. B. Johnston, and K. B. Hicks. 2003. *Increase in dry grind ethanol yield by converting fiber into ethanol.* American Society of Agricultural Engineers (ASAE) Meeting Paper Number 036065.

St. Joseph, Missouri, USA.

Singh, V., B. S. Dien, D. B. Jonston, K. B. Hicks, and M. A. Cotta. 2004. *A comparison between conversion of pericarp and endosperm fiber from corn into ethanol.* American Society of Agricultural Engineers (ASAE) Meeting Paper Number 046056. St. Joseph, Missouri, USA.

Singh, V., R. A. Moreau, K. B. Hicks, R. L. Belyea, and C. H. Staff. 2001*a*. Recovery of phytosterols from fiber removed from distiller dried grains with solubles (DDGS). *American Society of Agricultural Engineers (ASAE) Meeting Paper Number 016012.* St. Joseph, Missouri, USA.

Singh, V., R. A. Moreau, K. B. Hicks, R. L. Belyea, and C. H. Staff. 2002. Removal of fiber from distillers dried grains with solubles (DDGS) to increase value. *Transactions of the American Society of Agricultural Engineers (ASAE).* **45** (2):389-392.

Singh, V., K.D. Rausch, P. Yang, H. Shapouri, R. L. Belyea, and M. E. Tumbleson. 2001*b. Modified dry grind ethanol process.* American Society of Agricultural Engineers Report **2001-702.** Agricultural Engineering Department, University of Illinois at Urbana-Champaign, St. Joseph, Missouri, USA.

Tibelius, C. 1996. *Coproducts and near coproducts of fuel ethanol fermentation from grain.* Agriculture and Agri-Food Canada – Canadian green plan ethanol program: starchy waste streams evaluation project. Ottawa, Ontario, Canada. Available online at: http://res2.agr.ca/publications/cfar/index_e.htm .

University of Minnesota (UM). 2004. *The value and use of distillers dried grains with solubles (DDGS) in livestock and poultry feeds. St. Paul, Minnesota, USA.* Available online at: http://www.ddgs.umn.edu/.

van Everen, K., J. A. Maga, and K. Lorenz. 1992. Spaghetti products containing dried distillers grains. *Developments in Food Science* **29**:551-563.

Wahjudi, J., L. Xu, P. Wang, V. Singh, P. Buriak, K. D. Rausch, A. J. McAloon, M. E. Tumbleson, and S. R. Eckhoff. 2000. Quick fiber process: effect of mash temperature, dry solids, and residual germ on fiber yield and purity. *Cereal Chemistry* **77** (5):640-644.

Wall, J. S., Y. V. Wu, W. F. Kwolek, G. N. Bookwalter, and K. Warner. 1984. Corn distillers' grains and other by-products of alcohol production in blended foods. I. Compositional and nutritional studies. *Cereal Chemistry* **61**(6):504-509.

Weigel, J. C., D. Loy, and L. Kilmer. 2005. *Feed co-products of the dry corn milling process.* Iowa State University and Iowa Corn Promotion Board, Ames, Iowa, USA. Available online at: www.iowacorn.org/ethanol/ethanol_17.html.