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Updated Life Cycle Greenhouse Gas Data for Corn Ethanol Production

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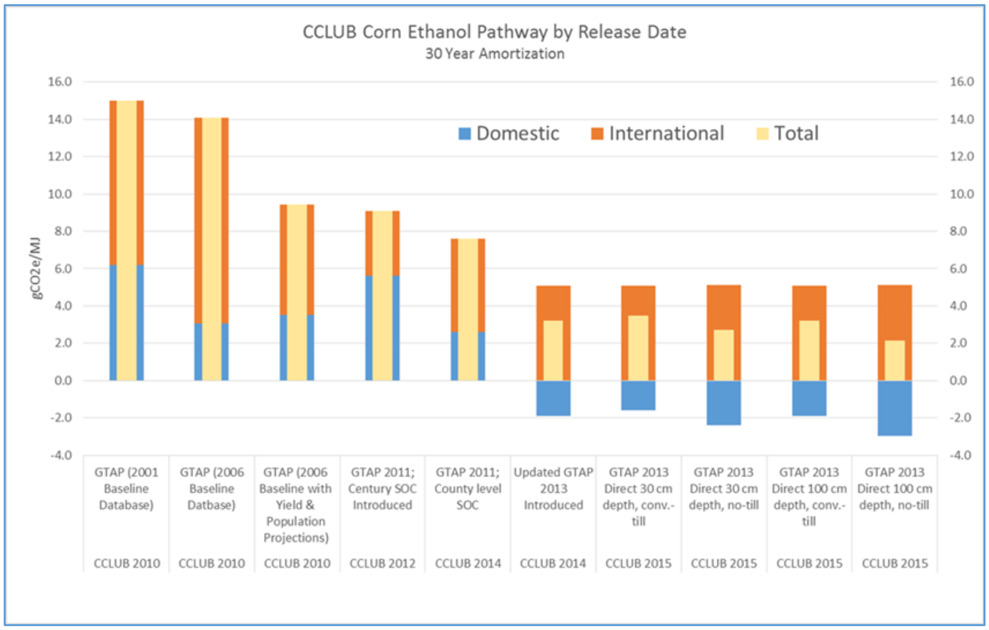
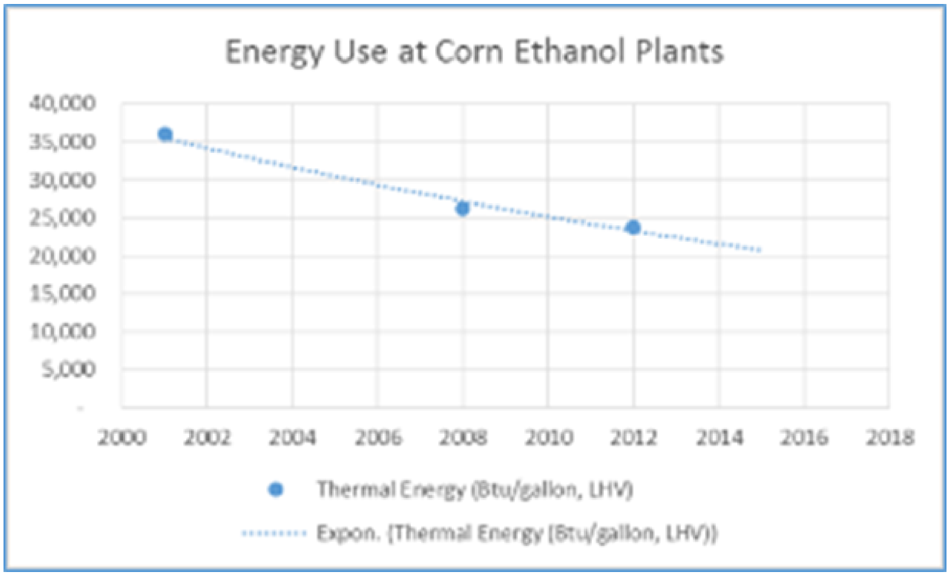
Executive Summary

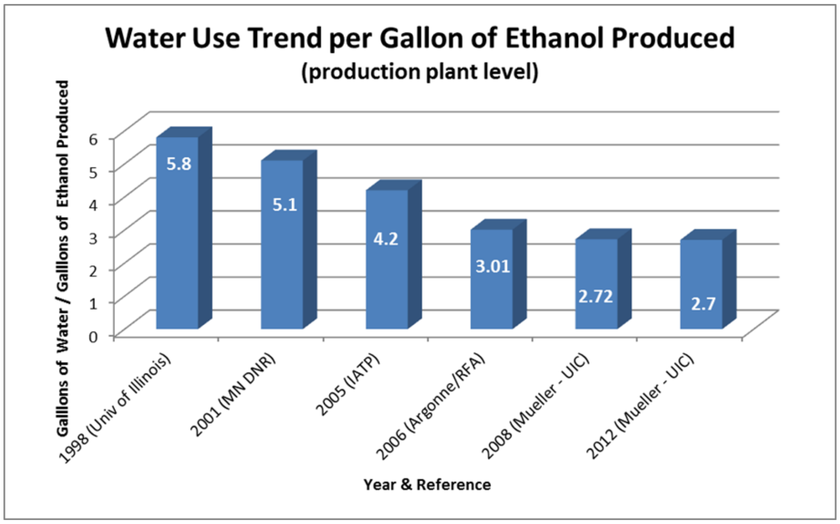
Significant progress in scientific research as well as technological advancements have shaped the corn ethanol industry since the Energy Independence and Security Act of 2007 expanded the Renewable Fuels Standard. This leaves early life cycle modeling efforts outdated. Some of the key research institutions that have furthered the science include Purdue University, Iowa State, University of Illinois, North Carolina State, South Dakota State, and others while the US Department of Energy, the US Department of Agriculture, and Argonne National Laboratory provided substantial research resources. We have reviewed the current, peer-reviewed literature published since 2010, after the finalization of the RFS2 modeling efforts. Model updates with the latest scientific findings and technological advances must be encouraged in order to document the continuous potential of selected biofuels including corn ethanol to reduce greenhouse gas emissions and to ensure the availability of export markets for this fuel.

Since the RFS2 modeling efforts emissions from land use change associated with an expansion of biofuels production have been continuously reexamined and are now in the range of 4-10 gCO_2e/MJ (down from >30 gCO_2e/MJ in the original RFS2 model) according to Argonne's GREET life cycle emissions model. Better databases and elasticity values in economic models that assess land use area changes and better carbon stock factors have significantly reduced the original emissions estimates.





Based on historic, surveyed trends, thermal energy consumption at 2015 corn ethanol plants are currently estimated to be (on average) 42% less than energy needs of 2001 plants. Better heat integration, co-product diversification, new enzyme technologies, and new grinding technologies have contributed to this trend.



Also, water consumption has been dramatically reduced since the early model dry grind plants were installed.

Total life cycle emissions from corn ethanol have also been reexamined in the context of land management practices and diverse fuel and feed coproducts associated with the pathway. GREET now also includes a combined stover and grain ethanol pathway. This latest data shows that ethanol produced at a combined grain and stover ethanol plant emits life cycle emissions of 50 gCO$_2$e/MJ. In a further refinement, GREET shows that ethanol produced on acres with either cover crops or manure as land management changes will produce emissions of 48 or 47 gCO$_2$e/MJ, respectively. This is a 50% reduction over gasoline.

Introduction

The COP21 meeting in Paris showcased the role that agriculture, biofuels, and soils can play in mitigating climate change.[1,2] Policy instruments are already in place at the domestic and international level that take advantage of biofuels' potential to reduce global warming. In the US the implementation of the California, and now Oregon, Low Carbon Fuel Standards (LCFS) and the expanded Renewable Fuels Standard (RFS2) have in fact prompted the implementation of low carbon technologies across biofuels production pathways and resulted in a significant increase in scientific studies and model updates related to corn ethanol greenhouse gas (GHG) assessments.

While both programs aim to replace gasoline with lower carbon fuels, the RFS2 specifically provides volumetric blending requirements for biofuels whereas fuel suppliers under the LCFS need to meet performance based GHG reduction targets from a fuel mix of their choice.[3] The RFS2 creates GHG reduction categories for four types of fuels: biomass-based diesel, cellulosic biofuel, advanced biofuel, and renewable/conventional fuel. For example, corn ethanol must meet a 20% lifecycle GHG reduction threshold, while advanced biofuels produced from qualifying biomass must meet a 50% reduction in GHG emissions. The LCFS in California requires a 10% reduction in the carbon intensity of transportation fuels by 2020.

Both the LCFS and RFS2 in the US rely on life cycle emissions analysis to ensure their policy objectives are met. Both programs employ different versions and parameterizations of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by Argonne National Laboratory. The latest version of Argonne's GREET emissions model released in September 2015 provides updated data for many fuel pathways including corn ethanol produced from grain and stover. GREET is the principal model used in the US for emissions assessments along a fuel's full production life cycle, which includes emissions from land use change (LUC), feedstock production, conversion, and combustion in the vehicle.[4] Both the RFS2 and the LCFS require the inclusion of emissions from LUC (both direct land use and indirect supply adjustments) as part of their regulatory structure.

European efforts under the "Fuel Quality Directive" are similar to the LCFS approach albeit with different GHG reduction targets, whereas Japanese efforts under the "Act on the Promotion of the Use of Nonfossil Energy Sources" are more in line with the RFS2 approach of volumetric blending requirements.

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[1] http://25x25blog.org/cop21-agreement-opens-the-door-for-solutions-from-the-land/

[2] http://newsroom.unfccc.int/lpaa/agriculture/join-the-41000-initiative-soils-for-food-security-and-climate/

[3] Transportation Research Board; "Policy Options for Reducing Energy Use and Greenhouse Gas Emissions from Transportation"; Special Report 307; 2011; available at www.trb.org

[4] GREET's parameterization flexibility provides substantial support to conduct life cycle assessments in compliance with international LCA standards includng "ISO 14040:2006 – Environmental management – Life cycle assessment – Principles and framework."

In Europe, due to the evolving science and uncertainties associated with quantifying emissions from land use change, the Fuel Quality Directive (which requires blending of biofuels with petroleum based fuels) does track but does not include emission from LUC in a fuel's GHG assessment. Corn ethanol must achieve a GHG reduction of 35% over gasoline (with an increasing threshold to 50% starting in 2018). However, biofuels must be certified for sustainable production based on an EU-approved certification protocol such as the one developed by International Sustainability and Carbon Certification (ISCC).[5]

Japan is increasing its biofuels blending volumes for gasoline over the next years.[6] Imported ethanol and ethyl tertiary butyl ether (ETBE) additives must meet a 50% reduction threshold of biofuels over gasoline set by the "Act on special accounts and the measures for the enhancement of the energy supply-demand structure." Emissions from LUC are considered but only those associated with direct LUC have to be included in the life cycle modeling effort.[7]

GHG assessments from life cycle models generally quantify emissions in terms of carbon dioxide equivalent emitted per mega joule of fuel produced, which allows a consistent comparison across pathways regardless of differing heating contents. The following sections of this report will detail some of the key scientific publications related to GHG emissions and sequestration effects from corn ethanol production with a focus on LUC and land demands, corn conversion, life cycle model boundary and accounting structures, as well as current life cycle emissions values for corn ethanol.

Many academic and government institutions including Purdue University, South Dakota State University, North Carolina State University, Iowa State University, US Department of Agriculture, Argonne National Laboratory/US Department of Energy have separately and collaboratively produced substantial research progress in this field. Throughout this report emphasis is placed on the most current, peer-reviewed literature published since 2010, after the finalization of the RFS2 modeling efforts.

The US Environmental Protection Agency during the RFS2 rulemaking process detailed the GHG emissions for its baseline dry grind ethanol plant. Figure 1 shows the pathway emissions by life cycle stage.[8] We will detail the latest scientific findings for each major life cycle stage that have occurred since then. Model updates with the latest scientific findings must be encouraged in order to document the continuous potential of selected biofuels including corn ethanol to reduce greenhouse gas emissions and to ensure the availability of export markets for this fuel.

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[5] http://iscc-system.org/en/

[6] http://www.platts.com/latest-news/oil/tokyo/japan-refiners-must-consume-500000-kl-biofuels-8206931

[7] Note that different gasoline baseline values and co-product allocation methods apply for Europe and Japan.

[8] Coordinating Research Council Inc, Transportation Fuel Life Cycle Analysis, A Review of Indirect Land Use Change and Agricultural N2O Emissions; CRC Report No. E-88-2, 2012, http://www.crcao.com/reports/recentstudies2012/E-88-2/CRC%20E-88-2%20Final%20Report.pdf

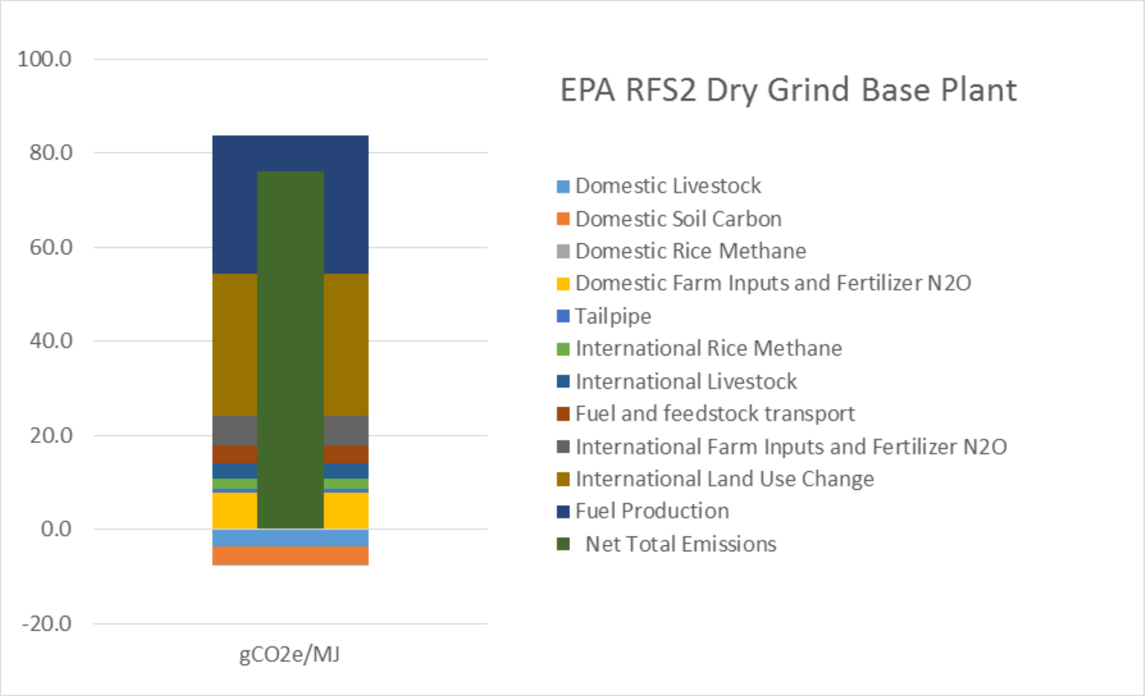

Figure 1: RFS2 GHG Emissions of Dry Grind Ethanol Plant by Life Cycle Stage

Domestic Soil Carbon and International Land Use Change

GREET has an interface called the CCLUB model that allows quantification of emissions from LUC associated with biofuels production. In CCLUB global land area changes are multiplied by carbon stock factors for different ecosystems and regions to derive total emissions associated with land use change. The first version of the CCLUB model was released in 2010. In this early version model land use area changes relied on Argonne-commissioned economic model runs based on the Global Trade and Analysis Project (GTAP) model and its 2001 database and carbon stock factors derived from Woods Hole for domestic and international LUC. The early CCLUB version only focused on corn ethanol production, but it did include options to assess carbon adjustments from different tillage practices and different biofuels production periods. Over the years CCLUB has been continuously refined to use updated land area data including new GTAP LUC results based on the 2013 Taheripour and Tyner publication with region-specific land transformation elasticities. This key effort by Purdue University resulted in much lower domestic land area changes than the older versions of CCLUB. This evolvement in domestic predicted land area changes has been independently confirmed by other modeling approaches.[9] Importantly, in a recent study by Iowa

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[9] Elliott, J., Sharma, B., Best N., Glotter., M., Dunn, J., Foster, I., Miguez, F., Mueller, S., Wang, M., A Spatial Modeling Framework to Evaluate Domestic Biofuel-Induced Potential Land Use Changes and Emissions, Environ. Sci. Technol., 2014, 48 (4), pp 2488–2496 DOI: 10.1021/es404546r

State University Babcock and Zabid provide compelling evidence that land use intensification has been widely underestimated in land use modeling resulting in overstated native land conversions by earlier land use models. [10]

Domestic carbon adjustments in the most recent GREET CCLUB version are modeled based on a surrogate Century biophysical soil carbon model at county level resolution. CCLUB now accommodates many biofuels feedstocks including biofuels produced from corn ethanol, stover ethanol, switchgrass, miscanthus, poplar and willow; introduction of expanded land management change scenarios for stover ethanol at 30% and 60% removal rates; carbon adjustments from cover cropping and manure application; display of national, AEZ and county-level soil carbon changes; and the use of different life cycle assessment (LCA) allocation methods (energy vs. mass allocation). Research at South Dakota State University, USDA, and elsewhere has shown that carbon sequestration effects from high rotation corn can significant.[11;12]

Figure 2 shows the different emissions results obtained over the years with different parameterization options. The graph shows that depending on the parameterization of the model the LUC values range from 4-10 gCO_2e/MJ. The Oregon Low Carbon Fuel Standard has adopted the CCLUB emissions factors associated with LUC from biofuels production. Table 1 shows the latest LUC research compared to the original RFS2 modeling efforts.

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[10] Bruce A. Babcock and Zabid Iqbal; "Using Recent Land Use Changes to Validate Land Use Change Models"; Staff Report 14-SR 109; Center for Agricultural and Rural Development; Iowa State University; 2014; available at http://www.card.iastate.edu/publications/dbs/pdffiles/14sr109.pdf

[11] Clay, David et al. "Tillage and Corn (Zea mays) Residue Harvesting Impact Surface and Subsurface Carbon Sequestration" Journal of Environmental Quality; Manuscript ID: JEQ-2014-07-0322-TR.R1; 2014

[12] Varvel and Wilhelm. "Long-Term Soil Organic Carbon as Affected by Tillage and Cropping Systems"; Soil Sci. Soc. Am. J. 74:915–921; 2010

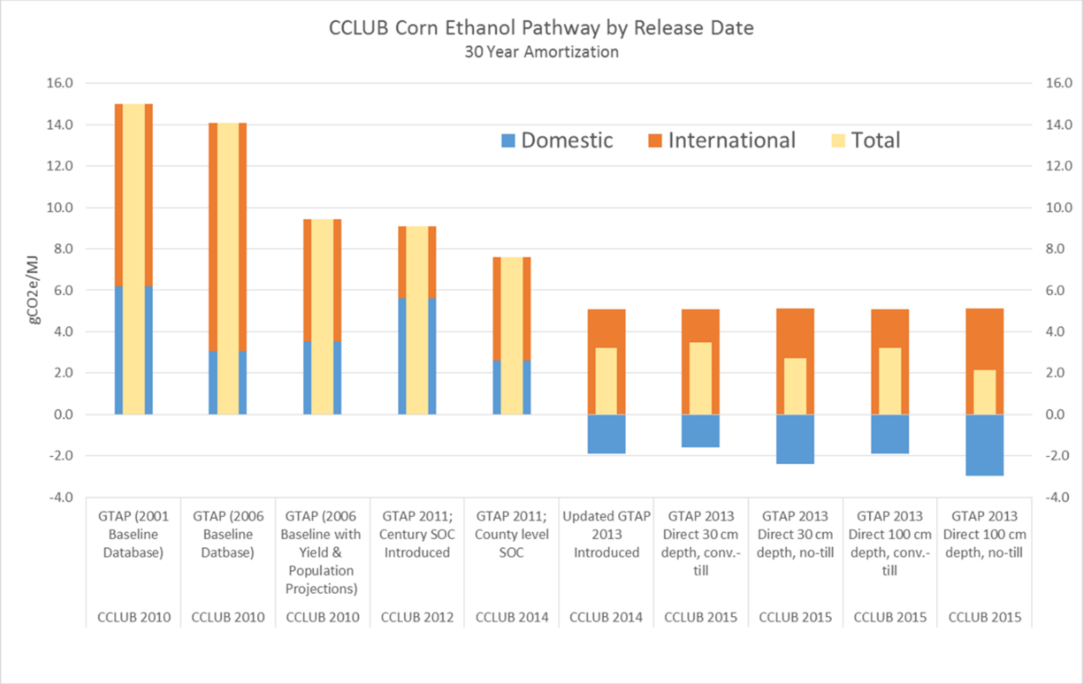

Figure 2: Emissions from Land Use Change in the CCLUB land use change interface to the GREET Model. Emissions from international and domestic land use change combined range from 4-10 gCO_2e/MJ depending on the parametrization of the model. Depending on the modeling assumptions (including the use of different conservation practices) domestic land use emissions are negative indicating carbon sequestration.

Table 1: Advances in LUC Research

	EPA RFS2 Values	**Latest Research**
	gCO_2e/MJ	
Domestic Soil Carbon	-3.8	
Domestic Rice Methane	-0.2	
Domestic	-4	-2 to +2
International Rice Methane	2.0	
International Land Use Change	30.2	
International	32.2	+6 to +8

Land Demands

A big debate is the extent to which cropland is expanding or contracting internationally as well as domestically and to what degree any movement along the agricultural frontier is related to biofuels production. Two recent reports attribute cropland expansion in sensitive regions like the

Prairie Pothole Region to increased land demands from biofuels production.[13,14] The paper by Lark et al. calls into question the United States Environmental Protection Agency's (USEPA) aggregate compliance approach that aims to limit cropland expansion. This mechanism requires USEPA to check the amount of US cropland against a 2007 baseline annually and work with USDA to identify underlying causes of LUC should the cropland acres in any year exceed that 2007 baseline (i.e., 402 million acres). Lark et al. conclude that 5.7 million acres of cropland has been converted from grasslands and an additional 1.6 million acres of cropland has been converted from long-standing prairie and range-like locations. While the Lark paper provides some key scientific insights into the use of geospatial tools for LUC assessments, a subsequent review of the paper and ongoing research by Lark and others will likely further refine these findings. [15]

In fact, some advanced tools that can provide further evidence that LUC has or has not taken place have recently become available, benefitted by significant advances in imaging data processing over the last 5 years. An imagery tool developed by Global Risk Assessment Services (GRAS) and Genscape, Inc. was recently released to the public.[16] The tool utilizes high resolution current and historic pictures from the National Agricultural Imaging program (NAIP) for US LUC assessments and satellite-derived enhanced vegetation index imagery for global land area changes. Use of this tool showed that while certain native conversions have taken place in the Prairie Pothole Region the extent is unknown and further research is needed.[17]

Confirming cropland expansion and reversion is important. However, establishing causality between conversion and expanded biofuels production proves more difficult. Mumm et al. point out that although 40.5% of corn grain was used in ethanol processing in 2011, only 25% of US corn acreage was attributable to ethanol when accounting for feed and co-product utilization.[18] To put this into perspective: the current net acre use for corn ethanol is less than 25 million acres compared to 310 million acres in principal crops and additional millions of acres in rangeland, grassland, and pastureland.

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[13] Lark T J, Meghan Salmon J and Gibbs H K; 2015; "Cropland expansion outpaces agricultural and biofuel policies in the United States"; Environ. Res. Lett. 10 044003

[14] Environmental Working Group; "Ethanol's Broken Promise: Using Less Corn Ethanol Reduces Greenhouse Gas Emissions"; March 2014; Available at http://www.ewg.org/research/ethanols-broken-promise

[15] https://www.gras-system.org/nc/gras-tool/genscape/

[16] https://www.gras-system.org/

[17] Jennifer B. Dunn, Steffen Mueller, Laurence Eaton, "Comments on Cropland expansion outpaces agricultural and biofuel policies in the United States"; April 29, 2015; available at https://greet.es.anl.gov/publication-comments-cropland-expansion

[18] Mumm et al. "Land usage attributed to corn ethanol production in the United States: sensitivity to technological advances in corn grain yield, ethanol conversion, and co-product utilization"; Biotechnology for Biofuels 2014, 7:61.

While biofuels production likely causes land area changes and therefore emissions adjustments, vast areas of other lands exist that can be used to maximize sequestration.[19] The low hanging fruit would not be to focus on the current net acres going into biofuels production but rather a conversion of abundant low carbon marginal lands to more effective carbon-sequestering biomass vegetation[20]. The productivity of marginal lands for that purpose has been documented and further research is underway.[21]

Yield Price Elasticity

A key variable in economic land use models that greatly affects the predicted global land area changes in response to a biofuels policy is called yield price elasticity. This variable describes the response of farmers to price signals. The economic land use change models used in LUC analyses indicate that higher demand for corn due to biofuels production will stabilize or at times increase corn prices. However, recent research conducted by North Carolina State University, University of Illinois at Urbana Champaign, and Purdue University confirms that higher commodity prices actually mitigate land use impacts because growers (in response to higher corn prices) invest in more productive technologies.[22,23,24]

Life Cycle Model Structure

Life cycle models like GREET or similar models (including, for example, Canada's GHGenius model) are highly peer reviewed and follow ISO methodology. However, a researcher at Michigan State University recently asserted that current life cycle models suffer from structural problems and inadequate boundary specifications.[25, 26] His viewpoint is that all fixed carbon should never be combusted (whether fossil or biofuels carbon) and that the available arable land should only be

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[19] Mueller, S., Ken Copenhaver, and Dan Begert "An Assessment of Available Lands for Biofuels Production in the United States Using USDA Cropland Data Layers"; Journal of Agricultural Extension and Rural Development Vol. 4(18), pp. 465-470, October 2012

[20] https://www.youtube.com/watch?v=91ks0GRQb4I

[21] Cai X., Zhang X., Wang D. (2011) Land availability for biofuel production. Environmental Science & Technology, 45, 334-339.

[22] Is Yield Endogenous to Price? An Empirical Evaluation of Inter and IntraSeasonal Corn Yield Response; Barry K. Goodwin, Michele Marra, Nicholas Piggott and Steffen Mueller; June 3, 2012. Available at: http://www.erc.uic.edu/PDF/mueller/2012_corn_ethanol_draft4_10_2013.pdf

[23] Taheripour and Tyner."GTAP Data Update, Forecasting and Backcasting in GTAP, and CRC Work on CARB Results"; Purdue University; October 27-28, 2015 http://www.wrh.crcao.com/workshops/LCA%20October%202015/Session%203/Tyner,%20Wally.pdf

[24] Ruiqing Miao, Madhu Khanna, and Haixiao Huang; "Responsiveness of Crop Yield and Acreage to Prices and Climate"; Am. J. Agr. Econ. first published online May 29, 2015 doi:10.1093/ajae/aav025

[25] John M. DeCicco; "The liquid carbon challenge: evolving views on transportation fuels and climate"; WIREs Energy Environ 2015, 4:98–114. doi: 10.1002/wene.133; Available at https://www.heartland.org/sites/default/files/decicco-2015-wiley_interdisciplinary_reviews_energy_and_environment.pdf

[26] Michael Wang, Wallace E. Tyner, Dan Williams, and Jennifer B. Dunn; "Comments on and Discussion of The Liquid Carbon Challenge: Evolving Views on Transportation Fuels and Climate"; March 2015; Available at: https://greet.es.anl.gov/publication-comments-liquid-carbon

used to maximize sequestration. He states "Biofuel proponents point out that productivity gains can minimize land-use impacts. However, productivity gains can also be directed toward more rapidly rebuilding terrestrial carbon stocks." In a testimony before a congressional subcommittee the researcher stated that the “government GREET model violates the conservation of mass.”

In response it is worth noting that the land use emissions factor of 4-10 gCO_2/MJ represents the emissions from carbon adjustments for a system before and after a biofuels shock occurs. This takes into account changes for above and below ground carbon as well as foregone sequestration and converts the net carbon difference into an emissions factor. The land use emissions factor is generally positive, meaning that biofuels production does produce additional land use emissions. In certain areas land use emissions can be negative, indicating a net sequestration from a transition to biofuels feedstocks—as oftentimes seen with feedstock production on marginal lands or under conservation practices.

Conversion Efficiencies

While land demands for biofuels production and the emissions associated with LUC oftentimes take center stage in the public discourse surrounding biofuels, the recent technical advances in feedstock production and conversion are frequently overlooked. Over the last 15 years ethanol production has seen significant efficiency improvements.[27] Modern energy and processing technologies such as sophisticated heat integration, combined heat and power technologies, variable frequency drives, advanced grinding technologies, various combinations of front and back end oil separation, and innovative ethanol and dried distillers grains (DDG) recovery have reduced the energy footprint of the corn ethanol production process.

A comprehensive industry survey conducted in 2012 showed that corn ethanol production uses 34% less thermal energy and 31% less electricity compared to 2001 while yield increased by 7% over this same time period.[28]

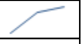
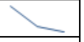
	2001	2008	2012	Trend
Yield (undenatured, gallon/bushel)	2.64	2.78	2.82	
Thermal Energy (Btu/gallon, LHV)	36,000	26,206	23,862	
Electricity Use (kWh/gallon)	1.09	0.73	0.75	
DDG Yield (dry) incl. corn oil (lbs/bu)		15.81	15.73	
Corn Oil Separated (lbs/bushel)	0	0.11	0.53	
Corn Oil Separated (% of Plants)	0%	33%	74%	
Water Use (gallon/gallon)	5	2.72	2.7	

Table 2: Efficiency Gains in Corn to Ethanol Processing

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[27] Shapouri, H. and James Duffield , Michael Wang. “The Energy Balance of Corn Ethanol: An Update”; USDA Office of Energy Policy and New Uses, AER-814, 2001.

[28] Mueller, Steffen. “US Corn Ethanol: Emerging Technologies at the Biorefinery and Field Level”; EESI Congressional Briefing. September 18, 2014. Washington, DC.

Since the last survey conducted in 2012 overall good liquidity and resilient operations did support continued investment in new technologies by plants. Some recent technology trends include corn kernel fiber to ethanol conversion, the co-location of biodiesel facilities with ethanol plants, diversification of co-products, new corn enzyme technologies, and general industrial energy efficiency improvements. For example, as pointed out in Ethanol Producer Magazine (EPM, 3/2016) Edeniq has installed its "Cellunator" technology at 6 ethanol plants, which provides better starch conversion. The technology can be retrofitted with Edeniq's "Pathway" corn kernel fiber technology to achieve a combined yield increase of 7%.[29]

Another technology that has been adopted by plants is Fiber By-Pass which separates corn fiber prior to fermentation (installed in at least 4 plants, see Fluid Quip in EPM 12/18/15) and selective grind technologies (installed in 11 plus plants).[30] As pointed out in Mueller and Kwik (2013) combinations of these technologies could result in about 5,000 Btu/gallon reduction in thermal energy (reduction of about 20% of total thermal energy needs). Note that increased co-product diversification generally also results in reduced drying energy. ICM is also very active in this field with its patented Advanced Oil Separation, patented Selective Milling Technology and patent-pending Fiber Separation Technology (EPM 10/2015).

Syngenta's Enogen product has directly incorporated enzymes into its corn traits. The technology is now used by 18 plants producing 1.3 billion gallon of corn ethanol (EPM 12/2015). According to Syngenta Enogen raises ethanol yield per bushel by up to 3%, reduces electricity use up to 3%, and lowers natural gas use up to 10%.

Good investment liquidity by ethanol plants since 2012 also resulted in upgrades of general industrial energy systems at ethanol plants including heat exchangers, combined heat and power technologies, and upgraded motors. An EPM article (2/2016) stated that Dresser-Rand has "installed about 50 steam turbine generator sets in various corn-to-ethanol plants in the U.S. and a few in other countries with "interest building again."

Results from the last three surveys (Figure 3) of the ethanol industry produced a close to linear trend in energy efficiency improvements at plants. Given the good liquidity in the industry over the last three years and the energy savings associated with many new technologies installed at plants a close to linear interpolation of plant efficiencies seems appropriate (note regression shows small, exponential characteristics of learning curves). This would indicate that the US corn ethanol industry of today, on average, consumes about 21,000 Btu/gallon of thermal energy (a 12% reduction over 2012 and a 42% reduction over 2001). Note that this is an average of all processes and plant types and includes facilities that sell wet DDGS. Financially, reduced energy costs and increased value from co-product diversification serves to stabilize and even increase margins. Table 3 shows the impact of plant efficiency improvements on the GHG profile compared to the original RFS2 modeling efforts.

Efficiency improvements during the corn production phase have also been documented. These include more accurate and targeted delivery of chemicals and agricultural inputs as well as modern high-yielding corn hybrids.

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[29] http://www.ethanolproducer.com/articles/13129/edeniq-cellunators-installed-at-nebraska-ethanol-plant

[30] http://ethanolproducer.com/articles/12861/ethanol-industry-outlook-on-2016

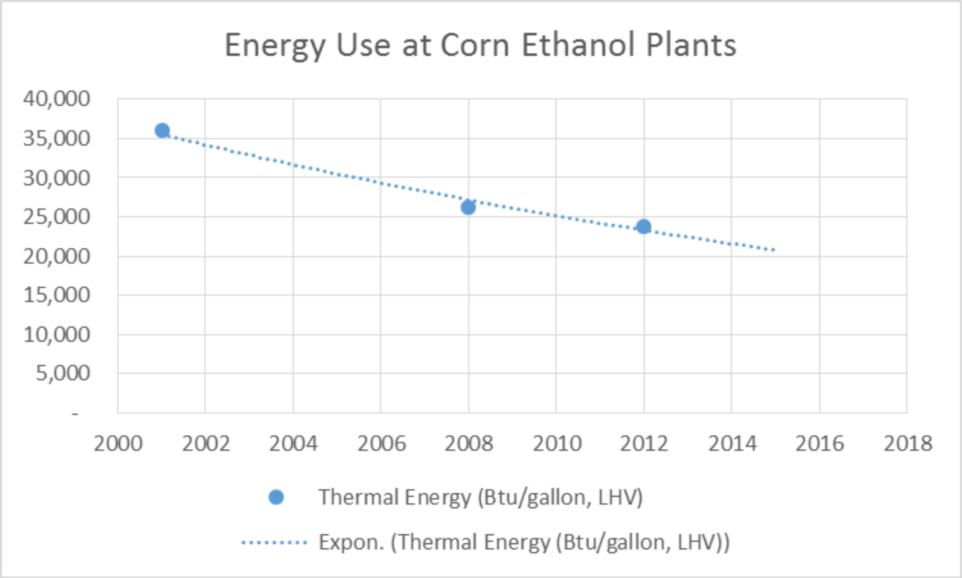

Figure 3: Projected Energy Efficiency Improvements based on Historic Trends

Table 3: Advances in Plant Efficiencies

	EPA RFS2 Values	Latest Research
	gCO_2e/MJ	
Domestic Soil Carbon	29.4	15-30*

**energy efficiency improvements and coproduct diversification have lead to a multitude of different plant pathways. Corn oil separation technology if sold into the biodiesel markets can generate significant co-product credits.*

Baseline Time Accounting

Another recent debate that has the potential to significantly influence the impact from LUC centers around the accounting method used for emissions over time. Researchers and regulatory agencies, including USEPA, have been assuming that biofuels production facilities will only exist up to 30 years and therefore the LUC models have “amortized” emissions over this time period. However, much longer operational periods for these facilities are likely. Separately, recent peer-reviewed research by Kloverpris and Mueller have suggested the use of a different emissions accounting method altogether. That method shows that increased biofuels production in an environment of future land use needs for food simply accelerates anticipated land use needs and by quantifying these effects avoids the use of an arbitrary amortization period. This alternate "baseline time accounting method" substantially reduces emissions (by up to 50%) associated with biofuels production.[31]

An attempt was made to refute the peer reviewed paper's findings in a letter to the editor.[32] The comments were refuted again by the authors in the same journal. Importantly, a recent peer reviewed paper by European researchers Schmidt, Weidema, and Brandao strongly but independently supported the key findings of the original publication, including the avoidance of an arbitrary amortization period.[33]

Current Life Cycle Modeling Results for Corn-based Ethanol

Life cycle methodologies have been refined to allow for proper treatment of the latest feedstock production and conversion practices.[34] Expansion of the model boundaries allows for proper accounting of co-products produced from an acre going into biofuels production, including stover removal for animal feed or cellulosic ethanol production. Corn oil separated at the front end or back end at an ethanol plant is often used as animal feed or as feedstock for biodiesel production. Finally, permanent soil carbon sequestration effects on high rotation corn acres have been considered in life cycle modeling efforts.

GREET shows that ethanol produced from corn grain and corn stover provides substantial GHG benefits over gasoline. The latest version of GREET benefits from updated soil carbon modeling results that provide more refined predictions of carbon stock changes from biofuels production as well as updated economic models that show reduced land area requirements for corn ethanol production.[35,36, 37] As a result, the latest version of GREET shows life cycle emissions for average

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[31] Jesper Hedal Kløverpris and Steffen Mueller; "Baseline time accounting: Considering global land use dynamics when estimating the climate impact of indirect land use change caused by biofuels"; Int J Life Cycle Assess DOI 10.1007/s11367-012-0488-6; published September 2012.

[32] Jeremy Martin; "Regarding your article "Baseline time accounting: considering global land use dynamics when estimating the climate impact of indirect land use change caused by biofuels." Int J Life Cycle Assess (2013) 18:1279 doi: 10.1007/s11367-012-0488-6

[33] *Jannick H. Schmidt` Bo P. Weidema, Miguel Brandao*; "A framework for modelling indirect land use changes in Life Cycle Assessment"; Journal of Cleaner Production xxx (2015) 1e9

[34] Steffen Mueller, Stefan Unnasch, Wallace E. Tyner, Jennifer Pont and Jane M-F Johnson; "Handling of co-products in life cycle analysis in an evolving co-product market: A case study with corn stover removal"; Advances in Applied Agricultural Science, Volume 03 (2015), Issue 05, 08-21

[35] Steffen Mueller and Jennifer Dunn; "Soil Carbon Sequestration and Land Use Change Associated with Biofuels Production"; presented at the CRC Workshop on Life Cycle Analysis of Transportation Fuels; Argonne National Laboratory, October 28, 2015

[36] Qin, Z., Dunn, J. B., Kwon, H., Mueller, S. and Wander, M. M. (2015;, "Soil carbon sequestration and land use change associated with biofuel production: empirical evidence"; GCB Bioenergy. doi: 10.1111/gcbb.12237

[37] Qin, Z., Dunn, J. B., Kwon, H., Mueller, S. and Wander, M. M. (2016); "Influence of spatially-dependent, modeled soil carbon emission factors on life-cycle greenhouse gas emissions of corn and cellulosic ethanol"; GCB Bioenergy. Accepted Author Manuscript. doi:10.1111/gcbb.12333

US produced corn ethanol in the range of 63.5–66.4 gCO$_2$e/MJ, which is over 30% less than the 94 gCO$_2$e/MJ value for gasoline.

GREET now also includes a combined stover and grain ethanol pathway.[38] This latest data shows that ethanol produced at a combined grain and stover ethanol plant emits life cycle emissions of 50 gCO$_2$e/MJ. In a further refinement, GREET shows that ethanol produced on acres with either cover crops or manure as land management changes (LMC) will produce emissions of 48 or 47 gCO$_2$e/MJ, respectively.[39] This is a 50% reduction over gasoline. A marginal allocation of emissions emphasizes the low GHG impact associated with stover removal.

Table 4: Life cycle emissions of combined grain and stover ethanol production

	LMC with LUC (g CO$_2$e MJ^{-1})				LMC without LUC (g CO$_2$e MJ^{-1})		
	Baseline	Cover crop	Manure		Baseline	Cover crop	Manure
Combined Gallon							
	50	48	47		44	42	42
Marginal Allocation							
Grain Ethanol	55	55	55		47	47	47
Stover Ethanol	30	17	12		31	18	12
Energy Allocation							
Grain Ethanol	52	50	50		44	41	42
Stover Ethanol	50	49	46		51	50	47

As mentioned in the introduction of this report, domestic policy instruments such as the RFS2 have helped reduce GHG emissions by fostering the use of biofuels. GREET has also been parameterized by researchers to document the overall savings. A recent study issued by the Renewable Fuels Association estimates biofuels consumed under the RFS2 have reduced U.S. GHG emissions by 354 million metric tons of CO$_2$e since 2008, which that study equates to the annual emissions from 74 million passenger cars.[40]

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[38] Zhangcai Qin, Christina E. Canter, Jennifer B. Dunn, Steffen Mueller, Ho-young Kwon, Jeongwoo Han, Michelle Wander, and Michael Wang; "Incorporating Agricultural Management Practices into the Assessment of Soil Carbon Change and Life-Cycle Greenhouse Gas Emissions of Corn Stover Ethanol Production"; Argonne National Laboratory, September 2015, ANL/ESD-15/26

[39] Steffen Mueller and Jennifer Dunn. "CCLUB Evolution"; GREET User Workshop, Argonne National Laboratory, October 15-16

[40] http://www.ethanolrfa.org/2015/11/analysis-rfs2-implementation-has-reduced-ghg-emissions-by-354-million-metric-tons/

Water Use

Figure 4 below shows the water use at ethanol plants (gallons of water per gallon of ethanol produced). Water use has decreased by half since the early dry grind plant installations[41,42,43,44]. Cooling water recycling, reverse osmosis, and reuse of filter backwash water are cited as technologies that contribute to this trend.[45]

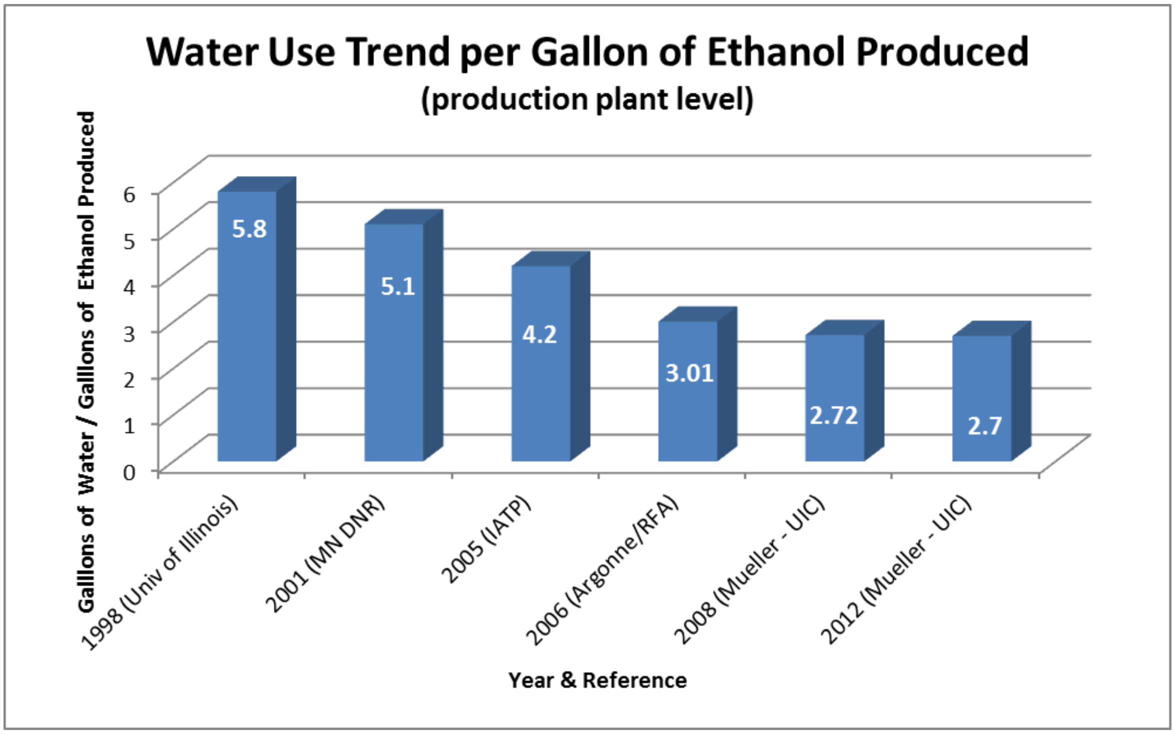

Figure 4: Trends in water use within ethanol plants (1998 – 2012). Source: Richard Nelson, KS State University

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[41] University of Illinois Extension. March 2009. Water Use for Ethanol Production

[42] Aden, Andy. September/October 2007. Water Usage for Current and Future Ethanol Production. Southwest Hydrology.

[43] http://ethanolrfa.org/page/-/PDFs/RFA%202013%20Ethanol%20Industry%20Outlook.pdf?nocdn=1

[44] Mueller, Steffen and Kwik, John. (2013). 2012 Corn Ethanol: Emerging Plant Energy and Environmental Technologies. University of Illinois – Chicago Energy Resources Center. Available online: http://www.erc.uic.edu/PDF/mueller/2012_corn_ethanol_draft4_10_2013.pdf.

[45] Ethanol Producer Magazine (6/2012); Dropping Water Use - Ethanol producers balance cost and conservation when reducing consumption, http://www.ethanolproducer.com/articles/8860/dropping-water-use