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Greenhouse Gas Reduction in Michigan Due to Ethanol Fuel Use

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Summary

Ethanol fuel is a renewable transportation fuel that displaces gasoline. Ethanol fuel production in the US is about 13 billion gallons per year. Currently, most ethanol fuel in the US is derived from corn grain. Ethanol fuel consumption in Michigan is over 450 million gallons per year, accounting for about 3% of the total ethanol fuel consumption in the US. More than 95% of ethanol fuel consumed in Michigan is produced via the corn dry milling process. Motor gasoline consumption in Michigan is about 4 billion gallons per year. Approximately 1% of the total motor gasoline consumption in Michigan is as fuel for boats.

The global warming intensity (GWI) of gasoline is about 101 kg CO_2 per million BTU, while the GWI of ethanol fuel used in Michigan is about 61 kg CO_2 per million BTU, not including indirect land use change (iLUC). (The effects of iLUC are not included because no scientifically reliable iLUC values are available at this time.) The annual greenhouse gas (GHG) reductions in Michigan due to use of ethanol fuel from 2007 to 2012 range from 0.9 to 1.4 million metric tons CO_2 ($MMTCO_2$) per year. The annual GHG reductions due to ethanol in boat fuel from 2007 to 2012 are about 0.013 – 0.018 MMT CO_2 per year. Since 2008, the annual GHG reduction due to ethanol fuel use in Michigan has exceeded 1 MMT CO_2 per year, which is equivalent to about 2% of the annual greenhouse gas emissions resulting from transportation in Michigan each year. The GHG reduction due to ethanol fuel use in Michigan accounts for about 3 - 4% of the total GHG reduction by ethanol fuel in the US over the same time period. One gallon of 100% ethanol fuel can eliminate about 6.7 pounds of CO_2 emissions in Michigan.

Table S1. GHG reduction due to ethanol fuel use in Michigan

Year	100% ethanol fuel consumption (Million gallons)	Overall GHG reduction ($MMTCO_2$ per year)	GHG reduction in boating ($MMTCO_2$ per year)	GHG emissions from transportation in Michigan¶ ($MMTCO_2$ per year)
2007	276	0.845	0.013	55.39
2008	378	1.154	0.015	51.36
2009	429	1.301	0.015	50.00
2010	456	1.391	0.018	49.88
2011	457	1.393	0.017	48.77
2012	452	1.378	0.018	48.43

¶ Data source: USEPA. State Energy CO_2 Emissions.

http://www.epa.gov/statelocalclimate/resources/state_energyco2inv.html.

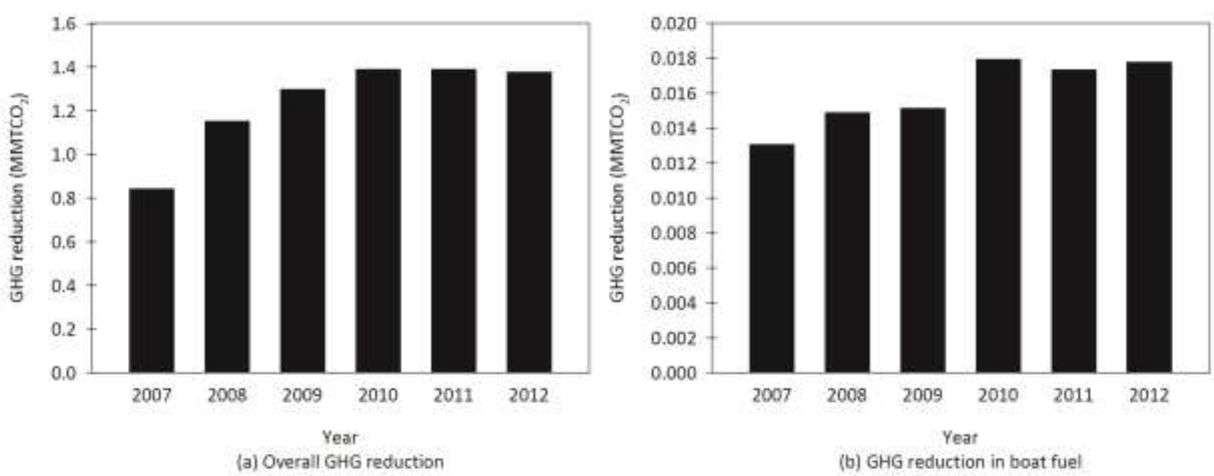

Figure S1. GHG reduction due to ethanol fuel use in Michigan

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1. Introduction

Ethanol fuel is a renewable transportation fuel that displaces gasoline. Ethanol production in the US is about 13 billion gallons per year[1]. Currently, most ethanol fuel consumed in the US is derived from corn grain. Some ethanol fuel is also derived from cellulosic feedstocks (e.g., crop residues, perennial grasses, woody materials, etc.). In the future more ethanol fuel will likely be derived from cellulosic feedstocks. Typically, corn-derived ethanol fuel can reduce life cycle greenhouse gas emissions (GHG) by 19 - 48% compared to GHG emissions of gasoline[2].

In this report, we estimate GHG reductions due to ethanol fuel use in Michigan from 2007 to 2012. First, gasoline and ethanol fuel consumption in Michigan is estimated from government statistics. We assume that ethanol fuel consumed in Michigan is derived from corn grain, not from cellulosic feedstocks. GHG emissions associated with gasoline and ethanol fuel are calculated from literature values. Based on fuel consumption data and GHG emissions associated with fuels, the GHG reductions due to ethanol fuel use are estimated.

A contentious issue in the life cycle GHG emissions of corn ethanol is indirect land use change (iLUC). iLUC is projected to occur when natural ecosystems elsewhere in the world are converted to croplands to produce the crops that are “lost” when they are converted to ethanol. iLUC cannot be measured directly; instead iLUC has been estimated via global agricultural economic models[3]. However, the current methodologies for estimating iLUC are based on a faulty assumption, a fundamental mathematical flaw[4]. As a result of this and other

[1] US EIA. Annual Energy Review. http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb1003

[2] Michael Wang et al. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environmental Research Letters 2012, 7 045905 doi:10.1088/1748-9326/7/4/045905.

[3] US EPA. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. Washington DC: US Environmental Protection Agency; 2010.

[4] Seungdo Kim, Bruce E. Dale, Reinout Heijungs, Adisa Azapagic, Tom Darlington, and Dennis Kahlbaum. Indirect Land Use Change and Biofuels: Mathematical Analysis Reveals a Fundamental Flaw in the Regulatory Approach. accepted in Biomass and Bioenergy 2014.

deficiencies[5,6,7] (e.g., nonlinear interactions with respect to biofuel volume, lack of data, inconsistent system boundaries between biofuel and petroleum systems, etc.) in estimating iLUC, no scientifically reliable iLUC values are available at this time. Therefore, we do not include iLUC values in our analysis of greenhouse gas emissions.

2. Gasoline and Ethanol Fuel Consumption in Michigan

Motor gasoline and ethanol fuel consumed in Michigan can be obtained from government statistics (i.e., USOHPI[8] and USEIA[9]) and are summarized in Table 1.

Table 1 Motor gasoline and ethanol fuel consumptions in Michigan (2007 – 2012)

Year	Total motor gasoline[8]§ (Million gallons)	Motor gasoline as boat fuel[8]§ (Million gallons)	100% ethanol fuel[9] (Million gallons)
2007	4,781	75	276
2008	4,598	60	378
2009	4,560	53	429
2010	4,547	59	456
2011	4,474	56	457
2012	4,460	58	452

§ Motor gasoline as it is consumed; includes fuel ethanol blended into motor gasoline.

The volume of gasoline used can be estimated by subtracting ethanol fuel volume from the total motor gasoline volume. It is assumed that E85 fuel is not used as a boat fuel. To estimate ethanol consumption in boat fuel, the volume of ethanol used in E85 fuel in Michigan was calculated using Equation 1. Results of the calculations are shown in Table 2.

[5] Edwards R, Mulligan D, Marelli L. Indirect Land Use Change from increased biofuels demand: Comparison of models and results for marginal biofuels production from different feedstocks. Ispra, Italy: European Commission, Joint Research Centre, Institute for Energy; 2010.
[6] Zilberman D, Hochman G, Rajagopal D. Indirect Land Use Change: A Second-best Solution to a First-class Problem. AgBioForum 2010; 13(4): 382–390.
[7] Finkbeiner M. Indirect land use change e Help beyond the hype?. Biomass Bioenerg 2014; 62: 218–221.
[8] US Office of Highway Policy Information. Highway Statistics Series. https://www.fhwa.dot.gov/policyinformation/statistics.cfm
[9] US EIA. State Profile and Energy Estimates. http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_use/total/use_tot_MIa.html&sid=Michigan

$$Ethanol_{E85} = Volume_{E85} \cdot HHV_{gasoline} / \left(\%_{ethanol} / \left(1-\%_{ethanol}\right) \cdot HHV_{gasoline} + HHV_{ethanol}\right) \qquad \text{Equation 1}$$

Where $Volume_{E85}$ is the gasoline energy-equivalent volume of E85. $Ethanol_{E85}$ is the volume of ethanol fuel consumed in E85. HHV is the higher heating value of the fuel; 120,439 BTU/gallon for gasoline and 84,530 BTU/gallon for ethanol [10]. The symbol $\%_{ethanol}$ represents the volumetric fraction of ethanol in E85 fuel (0.833[10]).

Table 2 E85 fuel consumption in Michigan[11] (2007 – 2011)

Year	E85 volume (Million gasoline-equivalent gallons)	Pure gasoline in E85 (Million gallons)	100% ethanol fuel in E85 (Million gallons)	E85 volume (Million gallons)
2007	1.5	0.34	1.7	2.0
2008	1.9	0.41	2.1	2.5
2009	2.0	0.45	2.3	2.7
2010	2.6	0.58	2.9	3.5
2011	4.0	0.89	4.5	5.4
2012	-	-	-	

Pure gasoline and ethanol fuel consumption in Michigan are summarized in Table 3 and Figure 1.

Table 3 Pure gasoline and ethanol fuel consumption in Michigan

Year	Overall		In boat fuel		Volumetric fraction of ethanol in ethanol blended motor gasoline fuel except E85 fuel
	Pure gasoline (Million gallons)	100% ethanol fuel (Million gallons)	Pure gasoline (Million gallons)	100% ethanol fuel (Million gallons)	
2007	4,505	276	70	4.3	5.7%
2008	4,220	378	55	4.9	8.2%
2009	4,131	429	48	5.0	9.4%

[10] Argonne National Laboratory. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Computer Model version 2013. Argonne, IL: Argonne National Laboratory.
[11] US EIA. Alternative Fuel Vehicle Data. http://www.eia.gov/renewable/afv/users.cfm

2010	4,090	456	53	5.9	10.0%
2011	4,017	457	51	5.7	10.1%
2012	4,008	452	52	5.8	10.1%¶

¶ assuming 2012 is the same as the volumetric fraction in year 2011

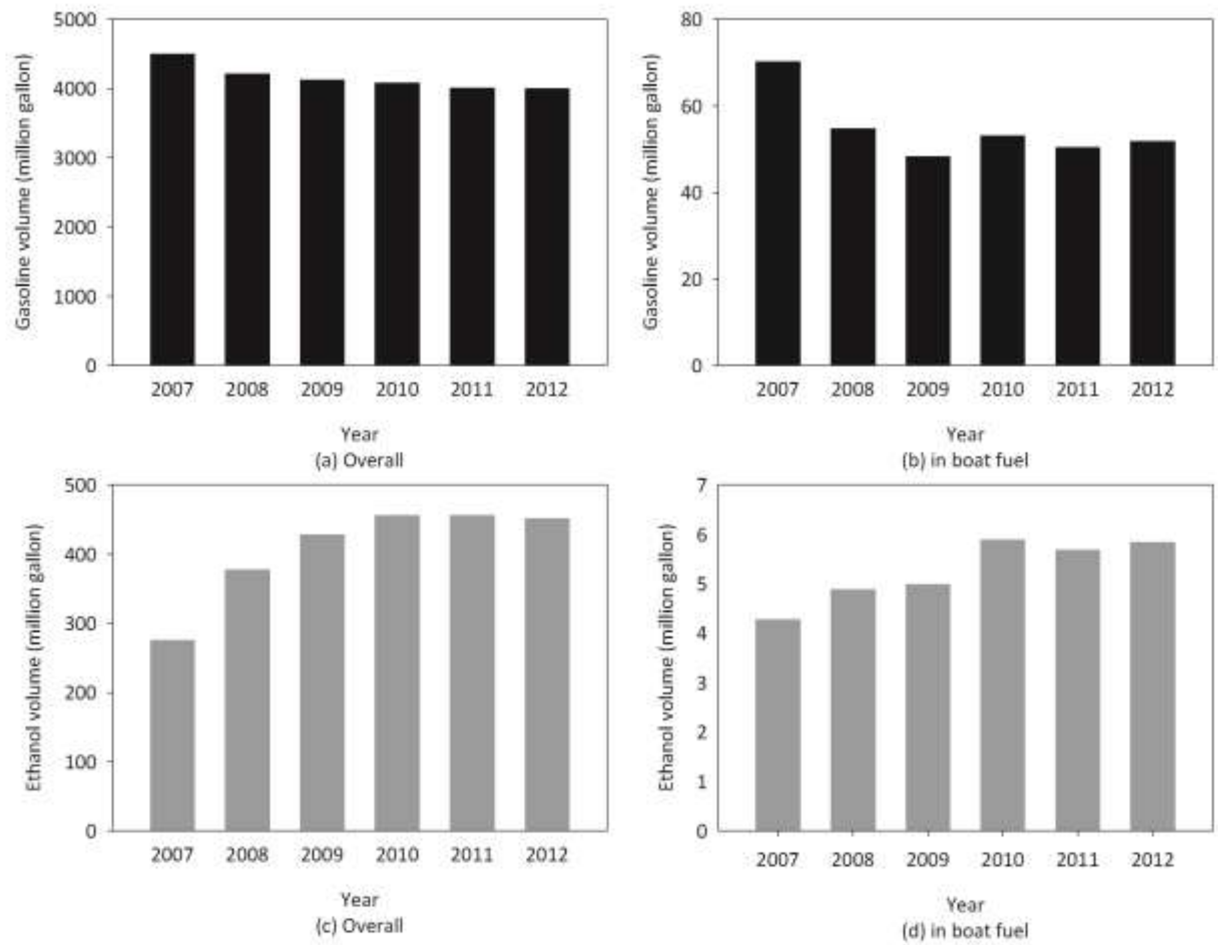

Figure 1 Pure gasoline and ethanol fuel consumption in Michigan

3. Corn Ethanol

Annual ethanol fuel production in Michigan is summarized in Table 4. There are five ethanol-producing, corn dry milling plants currently operating in Michigan as seen in Table 5. We assume that all ethanol fuel produced in Michigan is consumed in Michigan, and the rest of the ethanol required to meet our needs is imported from other states. It is also assumed that about 89%[10] of the imported ethanol fuel from other states is produced in dry milling plants. Overall more than 95% of ethanol fuel consumed in Michigan is produced via the corn dry milling process. The volume of ethanol fuel produced in Michigan by the corn dry milling process (and assumed to be consumed here also) is shown in Table 6.

Table 4 Annual ethanol fuel production in Michigan[9]

Year	100% ethanol fuel (Million gallons)
2007	186
2008	227
2009	215
2010	269
2011	275
2012	260

Table 5 Ethanol plants in Michigan[12]

Ethanol plant	Location	Operating Production (Million gallon per year)
Carbon Green Bioenergy Lake Odessa	Odessa, MI	55
Green Plains Renewable Energy	Riga, MI	60
Marysville Ethanol, LLC	Marysville, MI	50
POET Biorefining	Caro, MI	53
The Andersons Albion Ethanol LLC	Albion, MI	55

Table 6 Ethanol fuel used in Michigan

[12] RFA. Biorefinery Locations. http://www.ethanolrfa.org/bio-refinery-locations/

Year	100% ethanol fuel from corn dry milling (Million gallons)	100% ethanol fuel from corn wet milling (Million gallons)
2007	266	10
2008	361	17
2009	404	24
2010	435	21
2011	436	21
2012	431	22

4. Global Warming Intensity (GWI)

The global warming intensity (GWI) of a given fuel is the total GHG emissions associated with that fuel over its total life cycle, from cradle (well) to grave (wheel). GHG emissions associated with fuel production are obtained from the GREET model[10], while tailpipe emissions are obtained from RFS2[3]. National average GWI values are used in this analysis. GHG credits associated with co-products in ethanol production are estimated by the displacement method, in which GHG emissions associated with alternative products displaced by co-products are regarded as GHG credits. The GHG credits are then subtracted from the total GHG emissions of ethanol production to determine the GWI of ethanol. More detailed information on the GWI is presented in the Appendix.

The GWI values for gasoline and ethanol fuel are summarized in Table 7.

Table 7 GWI values

GWI [gram CO_2 equivalent per million BTU of the fuel§]		
Gasoline	Ethanol in dry milling	Ethanol in wet milling
100,702	60,029	75,925

§ based on lower heating value (LHV)[13]

Since the volumetric fraction of ethanol fuel from dry milling plants varies with year, the GWI values of ethanol fuel consumed in Michigan slightly varies with year as seen in Table 8.

[13] Lower heating value [10] - 112,194 BTU/gallon for gasoline; 76,330 BTU/gallon for ethanol

Table 8 GWI of ethanol fuel consumed in Michigan

Year	Volumetric fraction of ethanol from corn dry milling	GWI (gram CO_2 equivalent per million BTU)
2007	96.3%	60,622
2008	95.5%	60,752
2009	94.3%	60,933
2010	95.3%	60,772
2011	95.5%	60,751
2012	95.2%	60,798

5. Calculation

The GHG reduction due to ethanol fuel used in Michigan is the difference in GHG emissions between the current fuel mix scenario and the all-gasoline scenarios as estimated using Equation 2. The all- gasoline scenario is a system without ethanol fuel in motor fuel; thus, ethanol fuel in the current motor fuel mix is displaced by gasoline. The current fuel mix scenario is the current condition, in which ethanol fuel is blended in motor fuel.

$$\text{Reduction}_i = \text{GHG}_{\text{gasoline, i}} - \text{GHG}_{\text{ethanol, i}} \qquad \text{Equation 2}$$

Where $\text{GHG}_{\text{gasoline, i}}$ is the total GHG emissions of the i^{th} year in the gasoline scenario. $\text{GHG}_{\text{ethanol, i}}$ is the total GHG emissions of the i^{th} year in the current scenario. i is the time [year]. The total GHG emissions in both scenarios are estimated by Equations 3 and 4, respectively.

$$\text{GHG}_{\text{gasoline, i}} = \left(\text{BTU}_{\text{gasoline, i}} + \text{BTU}_{\text{ethanol, i}}\right) \cdot \text{GWI}_{\text{gasoline}} \qquad \text{Equation 3}$$

$$\text{GHG}_{\text{ethanol, i}} = \text{BTU}_{\text{gasoline, i}} \cdot \text{GWI}_{\text{gasoline}} + \text{BTU}_{\text{ethanol, i}} \cdot \text{GWI}_{\text{ethanol}} \qquad \text{Equation 4}$$

Where $\text{BTU}_{\text{gasoline, i}}$ is the total energy of gasoline consumed in the i^{th} year (based on LHV). $\text{BTU}_{\text{ethanol, i}}$ is the total energy of ethanol fuel consumed in the i^{th} year (based on LHV). $\text{GWI}_{\text{gasoline}}$ is the GWI of gasoline, and $\text{GWI}_{\text{ethanol}}$ is the GWI of ethanol. The GHG reduction becomes

$$\therefore\ Reduction_i = BTU_{ethanol,\,i} \cdot (GWI_{gasoline} - GWI_{ethanol}) \qquad \text{Equation 5}$$

The total energy consumption in the current scenario is summarized in Table 9.

Table 9 Total energy consumption for motor fuel use in Michigan (based on LHV)

	Overall (million BTU)			In boating (million BTU)		
	Gasoline $BTU_{gasoline,\,i}$	Ethanol fuel $BTU_{ethanol,\,i}$	Sum	Gasoline $BTU_{gasoline,\,i}$	Ethanol fuel $BTU_{ethanol,\,i}$	Sum
2007	505,442,578	21,072,118	526,514,696	7,884,865	326,758	8,211,622
2008	473,449,025	28,884,799	502,333,824	6,157,899	373,680	6,531,580
2009	463,482,426	32,715,801	496,198,227	5,427,343	381,128	5,808,471
2010	458,911,662	34,828,463	493,740,125	5,968,242	450,121	6,418,363
2011	450,693,711	34,866,933	485,560,644	5,671,453	434,575	6,106,028
2012	449,655,584	34,530,318	484,185,903	5,822,305	446,134	6,268,439

6. GHG reduction

With Table 7, Table 8 and Table 9, the GHG reductions due to ethanol fuel use in Michigan can be calculated. The corresponding results are shown in Table 10 and Figure 2. The annual GHG reductions in Michigan due to use of ethanol fuel from 2007 to 2012 range from 0.9 to 1.4 million metric tons CO_2 ($MMTCO_2$) per year. The annual GHG reductions due to ethanol in boat fuel from 2007 to 2012 are about 0.013 – 0.018 $MMTCO_2$ per year. Since 2008, the annual GHG reduction due to ethanol fuel use in Michigan has reached over 1 $MMTCO_2$ per year, which is equivalent to about 2% of the annual greenhouse gas emissions from transportation in Michigan over the same time period[14]. The GHG reduction due to ethanol fuel use in Michigan accounts for about 3 - 4% of the total GHG reduction in the US over the same time period. One gallon of 100% ethanol fuel can reduce total greenhouse gas emissions by about 6.7 pounds of CO_2 equivalents in Michigan.

Table 10 GHG reduction due to ethanol fuel use in Michigan

Year	100% ethanol fuel consumption (Million gallons)	Overall GHG reduction ($MMTCO_2$ per year)	GHG reduction in boating ($MMTCO_2$ per year)	GHG emissions from transportation in Michigan[14] ($MMTCO_2$ per year)
2007	276	0.845	0.013	55.39
2008	378	1.154	0.015	51.36
2009	429	1.301	0.015	50.00
2010	456	1.391	0.018	49.88
2011	457	1.393	0.017	48.77
2012	452	1.378	0.018	48.43

[14] USEPA. State Energy CO2 Emissions. http://www.epa.gov/statelocalclimate/resources/state_energyco2inv.html

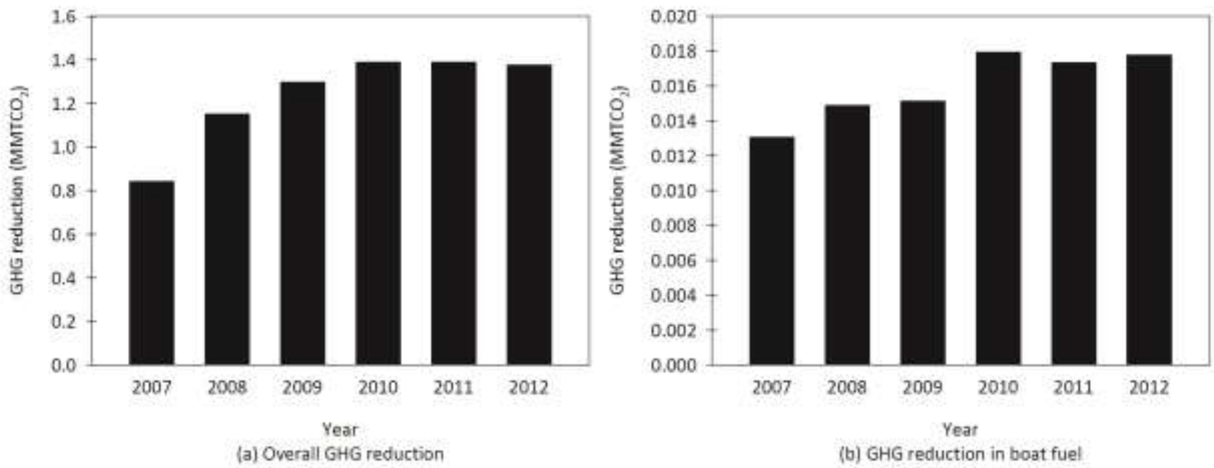

Figure 2 GHG reduction due to ethanol fuel use in Michigan

Appendix. Global Warming Intensity[10, 3]

Global warming potential

	Global warming potential
CH_4	25
N_2O	298
CO_2	1

Inputs in corn production

Agronomic input	N	P_2O_5	K_2O	$CaCO_3$	Herbicide	Insecticide
gram/bushel	415	148	172	1150	4.8	0.4

Fuel	Diesel fuel	Gasoline	Natural gas	Liquefied petroleum gas	Electricity
BTU/bushel	4730	1413	1301	1723	441

Soil emission

Soil N_2O emission = (N of N fertilizer + N contents in above and below ground biomass)* 1.525%*44/28

CO_2 emission from urea fertilizer = N fertilizer * % of urea (0.23) *44/12 *12/28

CO_2 emissions from CaCO3 =CaCO3*44/100

GHG emissions of corn

g CO_2/ bushel	Fuel	N	P2O5	K2O	CaCO3	Herbicide	Insecticide	TransportationΓ	Soil emissions
GHG	949	1,933	265	117	16	100	10	449	4,861

Γ 50-mile by a truck

Ethanol yield

	Dry milling	Wet milling
Ethanol yield (gallons per bushel of corn)	2.80	2.61

Fuel and material inputs in ethanol plant

Fuel and material	Dry milling	Wet milling
Natural gas (BTU/gallon)	22,378	34,372
Coal (BTU/gallon)	1,946	13,037
Electricity (BTU/gallon)	2,533	0
Alpha Amylase (gram/ gallon)	2.57	2.75
Gluco Amylase (gram/ gallon)	5.53	5.92
Yeast (gram/ gallon)	2.80	3.00

Co-products in ethanol plant

	Dry milling	Wet milling
DGS to animal feed (Bone-dry lb/gallon)	5.63	
CGM to animal feed (Bone-dry lb/gallon)		1.22
CGF to animal feed (Bone-dry lb/gallon)		5.28
Corn oil to animal feed (Bone-dry lb/gallon)		0.98

Displacement of conventional animal feed

Alternative product	Co-products (lb per lb of co-product)			
	Dry milling	Wet milling		
	DGS	CGF	CGM	Corn oil
Corn	0.78	1.00	1.53	
Soybean meal	0.31			
Urea	0.02	0.02	0.02	
Soybean oil				1.00

GHG emissions of ethanol plant

g per gallon	Dry milling	Wet milling
Process	2,368	3,932
Co-product credits	-1,032	-1,607
Total	1,336	2,326

Tailpipe emissions[3]

	Gasoline	ethanol
GHG (g/million BTU)	78,843	492

GWI of ethanol

	Dry milling	Wet milling
Feedstock§¶ (g CO_2 per gallon)	2,078	1,727
Ethanol plant¶ (g CO_2 per gallon)	2,370	3,934
Distribution and transportation (g CO_2 per gallon)	96	96
Tailpipe emission (g CO_2 per gallon)	38	38
GWI (g CO_2 per gallon)	4,582	5,795
GWI (g CO_2 per million BTU)Γ	60,029	75,925

§ including GHG credits of co-products

¶ including ethanol loss during distribution and transportation

Γ based on lower heating value – 76,330 BTU/gallon

GHG reduction due to ethanol fuel in US

Year	Ethanol fuel consumption (million gallons)	GHG reduction ($MMTCO_2$)	GHG reduction (millions of tons of CO_2)
2007	6,521	19.34	21.32
2008	9,309	27.61	30.44
2009	10,938	32.44	35.76
2010	13,298	39.44	43.48
2011	13,929	41.32	45.54
2012	13,218	39.21	43.22
2013	13,312	39.49	43.53