REASSESSMENT OF LIFE CYCLE GREENHOUSE GAS EMISSIONS FOR SOYBEAN BIODIESEL

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ABSTRACT. *This study updates the life cycle greenhouse gas (GHG) emissions for soybean biodiesel with revised system boundaries and the inclusion of indirect land use change using the most current set of agricultural data. The updated results showed that life cycle GHG emission from biodiesel use was reduced by 81.2% compared to 2005 baseline diesel. When the impacts of lime application and soil N_2O emissions were excluded for more direct comparison with prior results published by the National Renewable Energy Laboratory (NREL), the reduction was 85.4%. This is a significant improvement over the 78.5% GHG reduction reported in the NREL study. Agricultural lime accounted for 50.6% of GHG from all agricultural inputs. Soil N_2O accounted for 18.0% of total agricultural emissions. The improvement in overall GHG reduction was primarily due to lower agricultural energy usage and improved soybean crushing facilities. This study found that soybean meal and oil price data from the past ten years had a significant positive correlation ($R^2 = 0.73$); hence, it is argued that soybean meal and oil are both responsible for indirect land use change from increased soybean demand. It is concluded that when there is a strong price correlation among co-products, system boundary expansion without a proper co-product allocation for indirect land use change produces erroneous results. When the emissions associated with predicted indirect land use change were allocated and incorporated using U.S. EPA model data, the GHG reduction for biodiesel was 76.4% lower than 2005 baseline diesel.*

Keywords. *Biodiesel, Biofuel, Greenhouse gas emissions, Land use change, Life cycle analysis, Soybean.*

Biofuels are becoming popular alternatives to fossil fuels, with state and federal policies, such as the Renewable Fuel Standard (RFS2), significantly increasing their demand over the past several years (EPA, 2010a). Although biofuels have the potential to become completely renewable, their production with today's technology requires some nonrenewable resources, e.g., synthetic fertilizers are used to improve yields, and fossil fuels are used for powering farm equipment.

The first comprehensive life cycle inventory (LCI) for biodiesel (BD) produced in the U.S. from soybean oil was published by the National Renewable Energy Laboratory (NREL) (Sheehan et al., 1998). The purpose of the NREL study was to conduct a life cycle assessment (LCA) to quantify the energy and emissions associated with the production and use of soybean biodiesel and compare it to petroleum diesel. The study took into account the emissions associated with soybean agriculture, transport, crushing, oil transesterification, biodiesel transport, and use of biodiesel in a city bus. The study used 1990 soybean production data from the Farm Costs and Return Survey (FCRS) conducted by the USDA. The data for soybean crushing came from a performance study conducted in 1981. The study used a 1994 transesterification model from a single commercial transesterification facility.

The NREL study reported that soybean biodiesel reduced carbon dioxide (CO_2) emissions by 78.5% compared to petroleum diesel. The reason behind this reduction is that biomass-derived fuels participate in the relatively rapid cycling of carbon to and from the atmosphere. Biomass-derived carbon that ended up as CO_2 leaving the tailpipe of a city bus was subtracted from the total CO_2 as part of the biological recycling of carbon.

The objective of this study is to update the life cycle greenhouse gas (GHG) emissions calculations based on the most recent complete set of data for soybean biodiesel production via base catalyzed transesterification. Even though more current partial data for agriculture were available, the data used in this article are from 2006. It is important to use agricultural data from a single year, as agricultural data vary significantly from year to year depending on factors such as weather and pest infestation. The year 2006 was the most recent year that had a complete set of agriculture data available. This study compares the new LCA result with the NREL result and provides an explanation of the reasons for any differences. This study also points out the potential pitfalls of the system boundary expansion approach for impact assessment of indirect land use change, including the

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assumption that this approach will automatically account for co-product allocation.

METHODOLOGY

This study takes two different approaches; the first is the "base case," the methodology of which is consistent with the NREL's attributional LCA. Attributional LCA (ALCA) is a "business as usual" method that accounts for environmentally relevant physical flows to and from a product system. ALCA uses average values based on normal, current business practices. ALCA does not include any indirect effects that are not directly related to the production of biodiesel. The second approach is the "consequential" LCA, which includes factors such as indirect land use change. Consequential LCA (CLCA) aims to predict the consequences if changes are made to an established process. CLCA includes indirect changes in addition to direct effects.

The system boundary for the base case in this study is similar to that of the NREL study, except for inclusion of the use of agricultural lime (to improve soil pH) and soil nitrous oxide emission, and exclusion of oil transport. The list of inputs and outputs for the attributional LCA is shown in table 1. Agricultural lime was included in the base case because it is used periodically on soybeans and was inadvertently omitted from the NREL analysis. The impact of soybean oil transport was studied separately and not included in the base case because, for the most part, the soybean oil biodiesel plants considered in this study are co-located with soybean crushing plants. The GHG emissions were estimated from energy and material inputs in the production process. The emissions were calculated by multiplying the inputs by the corresponding emission factor. The data for estimating the effect of indirect land use change were borrowed from a recent EPA analysis (EPA, 2010b).

Three major anthropogenic greenhouse gases (CO_2, CH_4, and N_2O) were used to estimate the net GHG emissions. All emissions were reported as CO_2-equivalent (CO_2e) emissions. The CO_2e value indicates a GHG's global warming potential (GWP), as advocated by the Intergovernmental Panel on Climate Change (IPCC). GWP indicates the relative strength of radiative forcing (RF) of a GHG compared to CO_2 integrated over time. Therefore, CO_2 has a GWP of unity. The IPCC Second Annual Report

Table 1. Energy requirements of the inputs without co-product allocation.

Inputs	Quantity Used	Embedded Energy	gCO_2e Factor	gCO_2e [e]
Soybean agriculture	(per ha)			
Diesel	33.3 L [a]	35.9 MJ L^{-1} [b]	89.7 MJ^{-1} [c]	107,233.7
Gasoline	12.8 L [a]	32.4 MJ L^{-1} [b]	90.9 MJ^{-1} [c]	37,698.0
LP Gas	2.0 L [a]	23.7 MJ L^{-1} [b]	76.1 MJ^{-1} [d]	3,607.1
Natural gas	4.1 m^3 [a]	36.6 MJ m^{-3} [b]	72.4 MJ^{-1} [d]	10,864.3
Nitrogen	3.3 kg [a]	-	3.6 g^{-1} [d]	11,880.0
Phosphorus	12.1 kg [a]	-	1.2 g^{-1} [d]	14,520.0
Potassium	22.4 kg [a]	-	0.8 g^{-1} [d]	17,920.0
Lime	463.7 kg [a]	-	0.6 g^{-1} [b]	278,220.0
Seed	68.9 kg [a]	-	189.3 kg^{-1} [k]	13,042.8
Herbicide	1.6 kg [f]	-	25.8 g^{-1} [d]	41,280.0
Insecticide	0.04 kg [f]	-	30.0 g^{-1} [d]	1,200.0
Electricity	17.1 kWh [a]	3.6 MJ kWh^{-1} [g]	208.4 MJ^{-1} [d]	12,829.1
			Subtotal:	550,295.0
Soil N_2O emission	(per ha)			120,468.5
Soybean transport	(per ha)			56,464.3
Soybean crushing	(per L of BD)			
Electricity	212.3 Wh [h]	3.6 MJ kWh^{-1} [g]	208.4 MJ^{-1} [d]	159.3
Natural gas	0.11 m^3 [h]	36.6 MJ m^{-3} [b]	72.4 MJ^{-1} [d]	291.5
Hexane	11.1 g [h]	-	0.2 g^{-1} [b]	2.2
			Subtotal:	453.0
Biodiesel conversion	(per L of BD)			
Electricity	44.6 Wh [h]	3.6 MJ kWh^{-1} [g]	208.4 MJ^{-1} [d]	33.4
Steam at 10.3 bar (150 psi)	124.1 g [h]	2.0 MJ kg^{-1} [i]	119.1 MJ^{-1} [j]	29.6
Methanol	96.7 g [h]	20.1 MJ kg^{-1} [d]	67.7 MJ^{-1} [d]	131.6
Sodium methylate	2.7 g [h]	-	7.9 g^{-1} [k]	21.3
Hydrochloric acid	0.5 g [h]	-	13.5 g^{-1} [k]	6.8
			Subtotal:	222.7
Biodiesel transport and distribution	(per L of BD)			22.5
Biodiesel combustion	(per L of BD)			21.7

[a] 2006 ARMS and ERS data (data were obtained from the USDA through special request).
[b] ANL, 2010.
[c] DOE, 2008.
[d] EPA, 2010d.
[e] Product of columns 2, 3 (when applicable), 4, and proper unit conversion factor to get emission in gCO_2e.
[f] NASS, 2007.
[g] Direct unit conversion.
[h] ARS model.
[i] Steam table data.
[j] Natural gas as fuel with 60.8% boiler efficiency (steam generation at 150 psig = 1411 Btu lb^{-1}, and the enthalpy of evaporation from the steam table = 858 Btu lb^{-1}, which gives the total natural gas to steam usage efficiency of 858/1411 = 60.8%).
[k] Sheehan et al., 1998.

(SAR) assesses the GWP of CH_4 as 21 and N_2O as 310 for a 100-year horizon (IPCC, 1996). The IPCC Third Assessment Report (TAR) re-evaluates the GWP of CH_4 as 23 and N_2O as 296 for the same time horizon (IPCC, 2001). The United Nations Framework Convention on Climate Change reporting guidelines for national inventories were updated in 2006 but continue to require the use of GWP values from the IPCC SAR (UNFCCC, 2006). This requirement of using SAR GWP values ensures that new estimates of aggregate GHG emissions are consistent with estimates developed prior to the publication of the IPCC TAR and the IPCC Fourth Assessment Report (AR4), which re-evaluates the GWP of CH_4 as 25 and N_2O as 298 (IPCC, 2007). In order to comply with UNFCCC reporting standards, this article uses SAR GWP values. The U.S. EPA also follows UNFCCC guideline and uses GWP values from SAR (EPA, 2010c) in its renewable fuel standard (RFS2) life cycle analysis.

The GHG emissions for soybean biodiesel production were expressed as grams of CO_2-equivalent (gCO_2e). The energy inputs were multiplied by the embedded energy (low heating value for all fossil fuels) of the input and then multiplied by the appropriate GHG factor (table 1). For the non-energy inputs, where energy equivalence is not applicable, the input was directly multiplied by the GHG factor to calculate gCO_2e. The results were compared with 2005 baseline diesel GHG emissions, as required by The Energy Independence and Security Act (EISA) of 2007, to quantify the relative benefits of soybean biodiesel.

Data Description and Assumptions

Soybean Agriculture

At the time of the Sheehan et al. (1998) study, the most recent soybean production data were from the USDA 1990 Farm Costs and Return Survey (FCRS). In this article, all farm input and direct energy data for soybean production are from 2006, the most recent set of soybean survey data available at the time of this study. Agricultural inputs and outputs, such as yields and use of pesticides, vary from year to year. Therefore, mixing and matching agricultural data from different years can produce an unrealistic picture. Temporal variation could be minimized by averaging several years of data, but complete sets of agricultural data are not generally available for multiple consecutive years. Therefore, a complete set of the most recent agriculture data from a single year was used in this study.

In order to ensure that 2006 was not an abnormal year, which could bias the result, we carried out a linear regression analysis on yields from 1980 to 2010. This analysis verified that the yield for 2006 was within the 95% confidence interval (36.4 to 48.8 bu ac^{-1}) of predicted yield. The fertilizer, lime use, and direct energy use (such as diesel, gasoline, and natural gas consumption) were from the 2006 Agricultural Resource Management Survey (ARMS) and National Agricultural Statistics Service (NASS) data compiled by the USDA Economic Research Service (ERS). Chemical data for 2006 were from a chemical survey conducted by NASS (NASS, 2007). The 2006 ARMS and NASS soybean survey provided detailed state-level data for 19 major U.S. states. The state soybean yield data were estimates reported by NASS (NASS, 2010). The national average yield was 2906.7 kg ha^{-1} (43.2 bu ac^{-1}) in 2006. The soybean farm survey data were weighted by state acreage to derive the average quantity used for U.S. soybean production. The CO_2e emission values were from the Excel sheet "emission factors" in EPA data (EPA, 2010d). The CO_2, CH_4, and N_2O emissions for hexane and agricultural lime, not provided in the EPA report, were from the Excel sheet "BD" in the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model (ANL, 2010). These CO_2e emission values were then converted to CO_2e factors using SAR GWP values.

Soil Emission Data

This study used soil N_2O emissions (not available at the time of the NREL study) from the GREET model (ANL, 2010). N_2O is emitted through (1) direct emissions (including nitrification, denitrification, and volatilization) from the soil to the air, and (2) indirect emissions (including leaching and runoff of nitrate into waters) (Huo et al., 2009). N_2O emissions from the biological fixation of nitrogen are not included in the model, as the IPCC, in the 2006 guidelines, removed biological fixation of nitrogen as a direct source of N_2O (IPCC, 2006).

The GREET model (ANL, 2010) estimates soil N_2O emission using the total amount of nitrogen in the soybean biomass left in soybean fields (aboveground and belowground biomass) and in the nitrogen fertilizer applied. GREET estimates 7.4 g of nitrogen in the biomass per kilogram of soybean produced (200.7 g N bu^{-1} soybean). IPCC suggests an average conversion factor of 1% for the production of N_2O from biomass nitrogen and fertilizer nitrogen (IPCC, 2006). To estimate the total N_2O emission, 1% of the summed nitrogen content from biomass and synthetic fertilizer was multiplied by the factor 1.57 to account for the ratio of the molecular weights of N_2O and N_2, per IPCC recommendations. Using values from the GREET model, the N_2O emission from the soil was estimated to be 388.1 g N_2O ha^{-1} (3.63 g N_2O bu^{-1}).

Soybean Transport

The average hauling distance for soybeans from the point of production to that of processing depends on the crushing capacity of the plant. For an oil crushing plant with an annual capacity of 378 million L (100 million gal), the theoretical minimum hauling distance was calculated to be 56 km (35 mi), assuming a corn-soybean rotation and that the crushing plant was located at the center of a square-shaped agricultural area from which it draws the soybeans (Biodiesel Education, 2012). Because of system inefficiencies, the actual hauling distance would be greater than this. A one-way trip of 81 km (50 mi) was assumed to be the average distance to haul soybeans to the crushing/biodiesel plant using a truck as the mode of transportation (ANL, 2010). This estimation was based on 16 km (10 mi) to transport soybeans from farm to storage and another 64 km (40 mi) to transport soybeans to the crushing/biodiesel plant. The GREET model estimates of CO_2, CH_4, and N_2O emissions for soybean transportation were 512.32, 0.5886, and 0.0133 g bu^{-1}, respectively. Using SAR GWP, the CO_2e for soybean transport was estimated to be 56,464.3 g ha^{-1}

(529 g bu^{-1}) (table 1). The theoretical analysis provided a means of data verification.

Soybean Oil Extraction and Transesterification

This study uses the energy input data for soybean crushing, hexane extraction of the oil, and biodiesel production via alkali-catalyzed transesterification from a biodiesel plant model developed by the USDA-ARS using SuperPro designer (Intelligen, Inc., Scotch Plains, N.J.). The ARS model was prepared from process designs, equipment specifications, costs, and energy consumptions that were provided by technical experts and equipment suppliers to the soybean crushing and biodiesel industry. The model estimates the electrical and thermal energy inputs required for hexane extraction and its subsequent refining and conversion to biodiesel at an annual scale of 38.6 million L (10.2 million gal) of biodiesel, 137,491 Mg of soybean meal, 8,167 Mg of soybean hulls, and 3,975 Mg of crude glycerin. The model used in the analysis allows the plant to generate its own steam from natural gas with a life cycle efficiency of 60.8% (table 1). The model does not represent an industry average, but it provides a blueprint of a specific biodiesel plant based on the best information available from equipment manufacturers and communication with the industry.

Biodiesel Transport, Distribution, and Combustion

The biodiesel transport and distribution data used in this study were taken from the GREET model (ANL, 2010), which estimates a one-way trip of 540 km (335 mi) for biodiesel transport and distribution using a combination of truck, barge, and rail. This estimation was based on 52 km (32 mi) by truck, 68 km (42 mi) by barge, and 373 km (232 mi) by rail to transport the biodiesel to a distribution center, and another 48 km (30 mi) by truck to transport the biodiesel to its final destination. The GREET estimates of CO_2, CH_4, and N_2O emissions for biodiesel transport and distribution were 704.7, 0.81, and 0.0167 g $mmBtu^{-1}$ BD, respectively. Using SAR GWP, the CO_2e for biodiesel transport and distribution was estimated to be 0.7 g MJ^{-1} fuel (22.5 g L^{-1} BD) (table 1).

The CO_2 emission from biodiesel combustion was not included in the model because it is assumed to be equal to the amount of CO_2 captured by soybeans during photosynthesis. Exclusion of CO_2 emission is consistent with the NREL study. The combined N_2O and CH_4 emission from biodiesel combustion was estimated to be 21.7 gCO_2e L^{-1} BD (EPA, 2010d) (table 1).

CO-PRODUCT ALLOCATION

In order to provide a consistent comparison to the NREL report, this study used a mass-based allocation method that allocates energy and emissions to the various co-products by their relative weights. The USDA Economic Research Service (ERS, 2009) reported a 2006-2007 U.S. average oil yield of 0.189 kg oil kg^{-1} soybean (11.34 lb bu^{-1}). This extraction rate is higher than the 0.169 kg oil kg^{-1} soybean (10.16 lb bu^{-1}) used in the NREL study. The oil extraction rate for crop year 2006-2007 was used in this study in order to be consistent with the 2006 ARMS agricultural input data. After excluding the hulls and waste material, the soybean produced 20.5% oil and 79.5% meal by weight. Total emissions from biodiesel were allocated between oil and meal accordingly.

Table 2. Base case emissions for biodiesel with co-product allocation.

Subsystem	Allocation Factor (%)	Emissions (gCO_2e GJ^{-1} biodiesel) Before Allocation[a]	After Allocation
Soybean agriculture	18.4	28,128.9	5,175.7
Soil N_2O emission	18.4	6,157.9	1,133.1
Soybean transport	18.4	2,886.2	531.1
Oil recovery	18.4	13,853.2	2,549.0
Biodiesel conversion	89.9	6,810.4	6,122.5
Biodiesel transport	100	688.1	688.1
Biodiesel combustion	100	663.1	663.1
Total		59,187.8	16,862.6
Diesel emissions (gCO_2e GJ^{-1} diesel)[b]			89,668.2
GHG reduction for biodiesel relative to diesel (%)			81.2

[a] From table 1 (last column of table 1 was converted to gCO_2e GJ^{-1} biodiesel using conversion factors of 19,563.3 MJ of energy from biodiesel ha^{-1} and 32.7 MJ L^{-1} of biodiesel).

[b] DOE, 2008.

Transesterification of soybean oil produces biodiesel and crude glycerin. The NREL model of transesterification used a biodiesel to crude glycerin production ratio of 4.7:1 (10,504 kg h^{-1} for biodiesel and 2,235 kg h^{-1} for crude glycerin). According to this ratio, the NREL study allocated 82.4% to biodiesel and 17.6% to crude glycerin. However, modern plants have biodiesel to crude glycerin ratios of about 10:1 by weight (da Silva et al., 2009; Thompson and He, 2006; Van Gerpen et al., 2006). The model in this study uses output rates of 4,256.3 kg h^{-1} for biodiesel and 479 kg h^{-1} for crude glycerin. This corresponds to a ratio of 89.9% biodiesel to 10.1% crude glycerin, which is close to the modern industrial average. The co-product share of crude glycerin was deducted from the estimated GHG emissions of soybean agriculture, soybean transport, and oil recovery. The overall allocation for soybean agriculture, soybean transport, and oil recovery was therefore 18.4% (20.5% × 89.9%), as shown in table 2.

RESULTS AND DISCUSSION

The average soybean yield was 2,907 kg ha^{-1} (43.2 bu ac^{-1}) in 2006 (NASS, 2010). With 0.189 kg oil kg^{-1} soybean and 96% conversion efficiency from oil to biodiesel by weight, each hectare of soybean production is equivalent to 598.7 L of biodiesel (64.12 gal BD ac^{-1}). Biodiesel has a lower heating value (LHV) of 32.7 MJ L^{-1} (Sheehan et al., 1998).

The gCO_2e values from table 1 were converted to consistent units of gCO_2e per GJ of biodiesel output (table 2). The conversion used was 1 ha of soybean production is equivalent to 19,563.3 MJ of energy from biodiesel.

The reduction in GHG emission (81.2%) compared to the reduction reported by NREL (78.5%) was mainly because of improved agricultural management practices and increased energy efficiency in soybean crushing. Since the time of the NREL study, soybean yield has consistently im-

proved due to genetically engineered varieties, improved chemical applications, and new management practices (Ash et al., 2006). For example, in conjunction with reduced chemical applications and improvements in management practices, fewer equipment trips across the fields are required. Largely as a result of this, diesel fuel use decreased from 49.4 L ha^{-1} (5.29 gal ac^{-1}) in 1990 to 33.3 L ha^{-1} in 2006, and gasoline use decreased from 29.0 to 12.8 L ha^{-1} during the same period. In addition, recently constructed soybean crushing facilities are more energy efficient than older facilities. For instance, since 2002, the U.S. EPA has required soybean plants to limit their hexane use (EPA, 2001). Currently acceptable levels of hexane loss are less than one-third of the level reported in the NREL study (Woerfel, 1995). As a consequence, the new hexane input value used in this study is one-half of that reported in the NREL study.

Effect of Adding Agricultural Lime

The NREL study did not consider the impact of agricultural lime usage on GHG production. Lime is added periodically to reduce soil acidity and to increase soybean yield. The average lime application for soybean production for crop year 2006 was 463.7 kg ha^{-1} (NASS, 2007). With 0.6 $gCO_2e\ g^{-1}$ applied lime ($CaCO_3$) (ANL, 2010), the CO_2 emission associated with lime use was estimated to be 278,220.0 $gCO_2e\ ha^{-1}$. The GHG emission for lime was mainly from mining and processing. Of all agricultural inputs, lime contributed the most GHG. In fact, the emission from lime was 50.6% of the total GHG from agriculture inputs and 2.5 times more than the emission from diesel use, the next largest source of GHG emissions from agricultural inputs. Therefore, lime adds a significant amount of GHG emission to the soybean biodiesel life cycle assessment. The inclusion of lime was also recommended by Landis et al. (2007). The main reason for this high emission from lime is that the quantity of lime applied is significantly higher than other inputs (table 1). If agricultural lime was not included, for a more direct comparison to the NREL report, then the GHG reduction from the use of biodiesel relative to petroleum diesel would have been 84.1%, compared to the 81.2% value in table 2.

Effect of Adding N_2O Emissions from Soils

The NREL estimate did not include soil N_2O emissions. N_2O emissions accounted for 18.0% of total GHG emission from soybean agriculture (emission from agricultural inputs plus soil N_2O). If soil N_2O emissions were not included in the base case study, then the reduction in GHG emission from the use of biodiesel would have been 82.5% rather than 81.2%. The soil N_2O emissions contribute 6.7% of total life cycle GHG emissions for biodiesel production, and hence cannot be neglected. If both lime and N_2O emission were excluded from the life cycle inventory, for a direct comparison with the NREL results, then the GHG reduction for biodiesel relative to petroleum diesel would have been 85.4%, compared to 78.5% reported in the NREL study.

Effect of Adding Soybean Oil Transport

The base case estimation did not include emissions associated with soybean oil transport because this study assumed that the soybean crushing facility and biodiesel conversion plant were co-located. However, several biodiesel plants purchase oil and transport it to their plant. The NREL study included oil transport in its life cycle inventory, which added 560.9 $gCO_2e\ GJ^{-1}$ BD for 919 km (571 mi) using rail as a mode of transportation. This is equivalent to 61.0 $gCO_2e\ GJ^{-1}$ BD for 100 km of oil transport. This is only 1% of the emissions for biodiesel conversion. Thus, if oil transport from the crushing site to the biodiesel production site is a short distance, then emissions from oil transport can be neglected without causing much error.

Effect of Land Use Change (LUC)

In addition to direct emissions, the 2007 EISA requires that calculations of life cycle GHG emissions include all significant indirect emissions, such as significant emissions from indirect land use changes (ILUC). The LUC estimates (both direct and indirect) used by the EPA include domestic and international land use conversions induced by increased consumption of renewable fuels in the U.S. A summary of the EPA calculations for GHG emissions from LUC is shown in table 3.

International land use change is land use change in all countries other than the U.S. How land is used is assumed to be determined by the relative profits from various activities. The EPA estimated the land use change impact with a 30-year horizon beyond the year 2022, when RFS2 is fully implemented, with a 0% discount rate for its rulemaking (EPA, 2010c). A 0% discount rate means that the GHG emissions today are worth the same as emissions 30 years from now. To calculate the annual land use change impact for the next 30 years, an emission average was calculated using the following equation:

$$\text{LUC\_GHG} = \frac{\sum_{n=0}^{29} \text{LUC}_n}{30} \quad (1)$$

where LUC_GHG is the annual GHG per GJ of biodiesel, and LUC_n is the GHG emission due to land use change in the nth year. Year 0 in equation 1 is the year 2022. The LUC_GHG value estimated from this equation using data

Table 3. Summary calculation of annual life cycle GHG emission from LUC for the year 2022 and beyond (Source: EPA, 2010b).

	Emission ($gCO_2e\ GJ^{-1}$ Biodiesel)[a]		
Emission Category	Year 0	Years 1-19	Years 20-99
International land use change	1,114,419	5,078	-114
Domestic soil carbon[b]	-252,977	0	0
Domestic livestock	-1,991	-1,991	-1,991
Domestic rice methane	-7,536	-7,536	-7,536
International farm inputs and fert. N_2O	5,120	5,120	5,120
International livestock	-6,100	-6,100	-6,100
International rice methane	2,066	2,066	2,066
Total	853,001	-3,363	-8,555

[a] The conversion factor 1 GJ = 0.948 mmBtu was used to convert to $gCO_2e\ GJ^{-1}$ biodiesel from the original EPA calculations.

[b] Average domestic soil carbon was used for years 1-19 and 20-99.

from table 3 is 23,452 $gCO_2e\ GJ^{-1}$ biodiesel. The EPA assumed that LUC_GHG in equation 1 is caused solely by the shift in the equilibrium of demand for soybean oil and that no allocation of land use change GHG to the co-products is needed (EPA, 2010e). In other words, increased demand for oil is the only driving force in shifting the equilibrium. This assumption is based on the economic principle that assumes when oil price goes up, more soybeans will be crushed, thus increasing the oil supply, and as a result, the supply of meal also increases. With a static demand for meal, as supply increases, the meal price would go down, in which case, it could be argued that the meal is not a driving factor in LUC. Contrary to this assumption, the recent price trend data for soybean meal and oil show that they both go up simultaneously.

The USDA-ERS price data for oil and meal over the past ten years were regressed. The prices of oil and meal had a statistically significant positive correlation, with $R^2 = 0.73$ ($p < 0.0018$) (fig. 1). Another source (IndexMundi, 2012) of historical monthly commodity price data showed that soybean oil and soybean meal prices had a positive correlation, with $R^2 = 0.80$ ($p < 0.0001$) for the period 2002 to 2012. Soybean prices also increased during the same period. The soybean meal price could have increased just because of the higher soybean prices, and the correlation we observed could thus have been just an artifact of an increasing soybean price. To test if this was the case, a relative increase in oil price was compared to a relative increase in meal price. It is important to compare the relative increases in price, as oil has a much higher price per unit of mass compared to meal. For a relative comparison, the prices of oil, meal, and soybean were normalized using equation 2:

$$\text{Normalized price} = \frac{\text{Price} - \text{Minimum price}}{\text{Maximum price} - \text{Minimum price}} \quad (2)$$

Equation 2 linearly scales the prices of oil, meal, and soybean between 0 and 1. The normalized prices for oil and meal were regressed with the normalized price of soybeans using equations 3 and 4:

$$\text{Normalized oil price} = a_1 + b_1 \times \text{Normalized soybean price} \quad (3)$$

$$\text{Normalized meal price} = a_2 + b_2 \times \text{Normalized soybean price} \quad (4)$$

The slopes of the linear lines (b_1 and b_2) represent the relative increase in the price of oil or meal compared to the price of soybeans. The regression analysis showed $b_1 = 0.94$ and $b_2 = 1.00$. This result tells us that the oil price increased by only 94 cents per dollar increase in the soybean price, whereas the meal price increased dollar per dollar with the soybean price. Since the slope of the normalized meal price (b_2) was greater than the slope of the normalized oil price, it was concluded that the relative price of meal was increasing at least as rapidly as the price of oil.

A strong positive correlation between meal and oil indicates that demand for meal and oil increase proportionally. From these results, it was concluded that the price of soybean meal is as strong an incentive to trigger LUC as soybean oil. If price is the driving force, then both meal and oil are the drivers for LUC. In the EPA analysis, the system was expanded to include soybean meal in the partial equilibrium model, which assumes constant meal use. The assumption of constant meal use effectively allocates all LUC emissions to soybean oil, as the model assumes that soybean oil is the only driving factor for LUC.

The strong positive correlation between oil and meal price shows that both co-products act together as a unified driving force in any resulting LUC impact. The extent to which meal should be held accountable for indirect land use change depends on the correlation between meal and oil prices. If there were no positive correlation, then oil price increases alone could be blamed for all indirect land use change, and all LUC_GHG could be attributed to oil, as was done in the EPA study (EPA, 2010d). However, since there is a statistically significant positive correlation between oil and meal prices, the LUC_GHG effects should be allocated to both meal and oil. Thus, equation 1 becomes:

$$\text{LUC\_GHG} = \frac{\sum_{n=0}^{29} \text{LUC}_n}{30} \times \text{Allocation factor} \quad (5)$$

where the allocation factor partitions the GHG impact to its meal and oil sources. This equation takes into account the fact that both soybean meal and oil are responsible for LUC_GHG, and it attempts to identify the proportion of this value that is attributable to soybean oil production. Assuming the same soybean oil allocation factor for indirect land use change that was applied for soybean agriculture (18.4%), the LUC_GHG was estimated to be 4,315 $gCO_2e\ GJ^{-1}$ BD (instead of the value of 23,452 $gCO_2e\ GJ^{-1}$ in the absence of allocation).

The reduction in GHG emissions from the use of biodiesel, compared to 2005 baseline diesel, was 76.4% after inclusion of LUC (compared to 81.2% before inclusion). The GHG reduction of 76.4% was significantly greater than

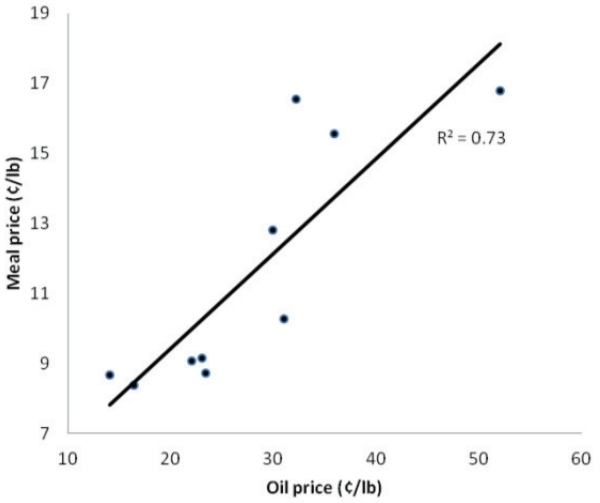

Figure 1. Annual average price of soybean oil and meal from 2000 to 2009 (source: ERS, 2011).

the 57% reduction reported by the EPA in its RFS2 rulemaking (EPA, 2010c). The difference arises from the application of the allocation factor to partition GHG impact between oil and meal. The EPA report assigned an allocation factor of 100% to soybean oil and hence to biodiesel. That is, the total GHG impact of land use change was attributed only to biofuel. If a similar assumption is made in this study, then the GHG reduction is estimated to be 55.0% which is close to the value of 57% that was reported by the EPA.

Summary and Conclusions

Using the most recent set of agricultural data available, from the 2006 crop year, soybean biodiesel production and usage were calculated to result in an 81.2% reduction of GHG emissions relative to those calculated for petroleum diesel usage based on 2005 data. This calculation incorporated agricultural lime application and soil N_2O emissions. If lime and N_2O were not included, for a more direct comparison with the 1998 NREL study, the reduction would have been 85.4%. This is a significant improvement over the 1998 NREL study, which reported a total GHG reduction of 78.5%. The improvement in GHG emission reductions was mainly due to reduced agricultural energy usage and improved energy efficiency in modern soybean crushing facilities.

The base case in this study used a similar system boundary as the 1998 NREL study, except that agricultural lime use and soil N_2O emissions were added, and soybean oil transport was omitted. Lime contributed about 50% of the total GHG emissions from soybean agriculture. The GHG emission from lime use was about 2.5 times higher than that of diesel use, the second highest contributor of GHG emissions from agricultural inputs. The emission from soil N_2O was about 18.0% of total emissions from agricultural and 6.7% of the total biodiesel life cycle GHG emissions. Therefore, it was concluded that soil N_2O emissions are significant and cannot be neglected. The impacts of oil transport were excluded from the base case in this study because most biodiesel plants are co-located with oil crushing facilities. The analysis revealed that GHG emission from oil transport of 100 km was equivalent to only 1% of the GHG emission from transesterification. Therefore, the GHG emission from oil transport for short distances could be neglected without causing much error in the final result.

Because soybean oil prices had a strong positive correlation with meal prices, it was argued that both meal and oil prices are responsible for shifting the equilibrium of soybean demand. Holding only soybean oil responsible for land use changes, with the assumption that soybean meal price does not change or decrease because of increased meal supply, was found to be erroneous. When the emissions associated with land use change (direct and indirect) were incorporated into the base case results, the net GHG reduction from biodiesel use was found to be 76.4% less than the emissions for 2005 baseline diesel.

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