The Lifecycle Carbon Footprint of Biofuels

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Estimating Greenhouse Gas Emissions from Soy-based US Biodiesel when Factoring in Emissions from Land Use Change

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The Importance of Emissions from Land Use Change

Lifecycle greenhouse gas calculations for biofuels have traditionally focused on engineering calculations of emissions from the production process. They have carefully analyzed the emissions involved in producing a feedstock through the use of tractors and fertilizer, refining the feedstock into oil, transporting the products, and burning the fuel in a vehicle. Although the greenhouse gas emissions from production have significant effects on total emissions, biofuels are ultimately a land use decision. The potential of biofuels to reduce greenhouse gas emissions originates with the capacity of land to remove carbon from the atmosphere. Biofuels have the theoretical potential to reduce greenhouse gas emissions because the growth of the feedstock takes the same amount of carbon out of the air that is released when the fuel is burned. By contrast, gasoline and diesel fuel take carbon out of the ground in the crude oil and release it to the air when the fuel is burned. Lifecycle analyses credit biofuels with this carbon removed from the atmosphere by growing the feedstock. In effect, they credit biofuels with the carbon benefit of the land used to grow them. Without this credit for the land use benefit, crop-based biofuels will generally result in an increase in greenhouse gas emissions, and cellulosic ethanol is projected to have roughly the same emissions as gasoline.

Producing biofuels is just one way of realizing the carbon benefit of land, *i.e.*, its capacity to remove carbon from the atmosphere. Used alternatively to grow forest, land sequesters carbon in tree trunks and soil. Using forest lands for biofuels foregoes ongoing sequestration in trees, releases most or all of the carbon in standing vegetation and much of the carbon in soils. Used to grow grasses, land sequesters carbon in the soil, which provides an immediate global warming benefit. Nearly all grasslands also provide forage for cows, sheep or goats, which feed us, and the same is true of land used to grow crops, which transforms atmospheric carbon into carbohydrates, proteins and fats. Feeding us is also a carbon benefit, and if lands that now feed us are diverted to other uses, we have to generate that carbon elsewhere – on other forest or grassland – sacrificing that other land's alternative carbon benefits.

To determine if biofuels really have the potential to reduce greenhouse gasses, the first requirement is that the carbon benefit of using land for biofuels must exceed the carbon benefit of land in its alternative, existing uses. Put another way, lifecycle analyses for biofuels should only credit the use of land to produce the biofuel if that use of land produces a net carbon benefit compared to its alternative likely land use. Unfortunately, most lifecycle analyses count the gross carbon benefit of using land for biofuels without deducting the cost (Searchinger *et al*. 2008; Farrell *et al*. 2007 (online supporting materials). They count the carbon sequestered in the feedstock but leave out the carbon storage and ongoing sequestration given up by taking land out of its existing use. This accounting is highly one-sided. It is equivalent to counting the economic benefit of using land to produce a crop without factoring in the rental cost.

Many previous analyses have noted qualitatively the potential of land use change to wipe out many or all of the carbon benefits of biofuels, but they have omitted the emissions from land use change in the quantitative analysis Farrell *et al*. (2007) (online supporting materials). (A number of such studies are set forth in Appendix A in the online supporting materials of Searchinger *et al*. 2008). They tend to present this land use change as a kind of secondary, unintentional effect that is hard to estimate but perhaps controllable. It is more helpful to view land use change as the intentional result of biofuels – if only the intentional change in using cropland for fuel instead of for food. From the standpoint of greenhouse gas accounting, making biofuels is a land use decision, and the first question is whether the use of land for biofuels removes and keeps more carbon from the atmosphere than its alternative. A proper lifecycle analysis must incorporate the

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emissions that occur from direct or indirect land use change to produce biofuels.

Estimating Emissions from Soy-Based Biodiesel

General Method

We have previously calculated the emissions from indirect land use change and incorporated them into the GREET life-cycle analysis (Argonne National Laboratory, 2007) for US corn and for switchgrass ethanol if it were produced on good American corn land (Searchinger *et al*., 2008). This analysis was based on formal, partial-equilibrium modeling by the Center for Agriculture and Rural Development at Iowa State, which takes into account shifts between crops, reductions in demands and different yields in different countries. We found that the emissions from land use change dominate the total emissions for biofuels. These emissions increase significantly by comparison with gasoline over a 30 year period.

Most estimates, however, find that corn-based ethanol has smaller greenhouse gas benefits (ignoring land use change) than other biofuels (Farrell *et al*., 2006). For this reason, corn-based ethanol has long been viewed as marginal. Biodiesel from soybeans, by contrast, has a much stronger environmental reputation. Part of this reputation stems from different air quality debates that dominated the discussion of ethanol ten years ago when the primary environmental concern with corn ethanol was a potential increase in emissions of precursors of low-level ozone. Biodiesel, by contrast, had significant ambient air benefits compared to diesel, leading to greater support among environmentalists. In addition, because soybeans require less fertilizer, and because the process of converting soybean oil to diesel fuel requires far less energy than converting corn to ethanol, most lifecycle analyses have found that soy biodiesel has far lower greenhouse gas emissions – generally generating savings of more than 50% compared to diesel or gasoline (Farrell *et al*., 2006).

Despite the greater savings from a pure engineering perspective, soybeans also require good cropland. Vegetable oil is a valuable food substance whose consumption has been growing on a worldwide basis, and whose rising prices have been reported as a major source of hardship in much of the world today (Bradsher, 2008). When soybean oil is diverted to biofuels, the vegetable oil will mostly be replaced, triggering emissions from land use change. Ideally, these emissions would be calculated using a worldwide, partial-equilibrium model that can calculate changes in demand and in production of a wide variety of substitutes, a model used in our corn calculations. At the time of writing, economists at Iowa State are working to adjust their model to evaluate worldwide vegetable oils more rigorously. In the absence of such a model, we believe however it is possible to calculate likely emissions from land use change using alternative scenarios to provide a clear picture of whether biodiesel from soybeans has the potential to generate true greenhouse gas savings when incorporating emissions from land use change. Even once more sophisticated models become available the simple approach applied here has the compensation of high transparency as outsiders can evaluate the potential emissions under different economic assumptions.

The emissions from land use change depend first on economic forces. Diverting soybean oil into biodiesel production will increase the price of soybean oil and other vegetable oils that are substitutes. As prices rise, their demand for purposes other than biofuels will somewhat decline – which creates other social costs but reduces the magnitude of increased emissions from land use change. Because most economic analyses find the elasticity of demand for categories of food products is low – as opposed to the elasticity of demand for one crop or oil – most diverted vegetable oil will be replaced, and in a free market, replacements crops will be provided in the cheapest way. Part will be replaced by increasing yields on existing lands, and part will be replaced by converting forest or grassland to new production – the amount of each depending on the cost. The level of land conversion will also depend on the yields of the new lands. With a few exceptions, the yields of corn, soybeans or rapeseed in the developing world do not match those in the United States and Europe, so shifting production abroad will require more land per unit of oil and therefore more land conversion.

The emissions from land use change will depend on the ecosystem converted. They include: (1) the loss of carbon in vegetation when forest or grassland is converted to produce biofuels directly or indirectly; (2) the loss of carbon in soils from that conversion; (3) the loss of ongoing carbon sequestration that would occur in forest or grassland if the land remained in its original use. To the extent that biofuels keep cropland in production that would otherwise leave production, the emissions include only the foregone carbon sequestration.

Emissions Estimates Assuming Full Replacement of Diverted Vegetable Oil Without Decreased Demand or Additional Yield Increases

Soybeans provide the primary feedstock for biodiesel in the United States. Many are exported and most of those used domestically are crushed. Crushing transforms 19% of the original soybean by weight into soybean oil,[2] and the remainder is transformed into soybean meal and other products, which are mostly used as animal feed but some are used as food additives. Biodiesel uses only the oil portion of the soybeans, leaving the remaining soybean products intact.

[2] According to Food and Agricultural Policy Research Institute (2007) baseline projections, in 2016/17 the United States will produce 85.065 million metric tons of soybeans and soybean crush of 54.874 million metric tons, producing 43.58 million metric tons of meal (79.4%) and 10.434 million metric tons of oil (19.0%). U.S. exports are expected to include 24.987 million metric tons of soybeans and 1.337 million metric tons of soybean oil. (See Table A1).

Producing more soy biodiesel in the United States could divert either soybeans in total or soybean oil. A liter (L) of biodiesel from soybean oil requires 0.362 bushels (bu) of soybeans, or 1.82 kilograms (kg) of oil. To produce the representative amount of 1 billion L of biodiesel from US soybeans would require 361,915,691 bu of soybeans (9.850 million metric tons (MT)) or 1,825,105,882 kg of oil (1.825 million MT). To analyze emissions from land use change, we first examined the emissions that would result from replacing diverted soybean oil under the following assumptions:

(1) there is no reduction in demand for vegetable oil for non-fuel uses,

(2) while crop yields continue to increase at current trends, the rise in prices will not trigger additional average yields because additional yield investments will only balance out use of more marginal land,

(3) oil diverted to soybeans comes entirely out of US oil exports proportionately to exports to the countries now importing these oils (Appendix Table B2);

(4) countries now importing soybeans from the United States import replacement vegetable oil in proportion to their present consumptive mix of vegetable oils, which may include some palm oil, sunflower oil and other kinds of oils in addition to soybean oil (Appendix Table B2),

(5) major exporting countries, including the United States, will supply the replacement oil in proportion to their present shares of world exports for each form of vegetable oil (Appendix Table B3).

We then calculated, as shown in Appendix Table B4, the amount of increased crop area required in each country to produce this additional amount of the relevant vegetable oil using Food and Agricultural Policy Research Institute (FAPRI)-predicted yields for 2016-17. Table B-6 shows the total amount of land required to produce the required level of vegetable oil.

As discussed for soybean oil, production of the feedstock for some vegetable oils will also produce large quantities of valuable by-products, as oil meal. The production of these by-products will reduce the amount of cropland required for other purposes, in particular the production of soybean meal reduces the amount of land required to produce animal feed. We therefore apportion the land needed to produce the additional soybeans or other feedstocks in part to the by-product and in part to the oil, using proportions by weight. In doing so, we assign soybeans only 19% of the increased cropland, and other crops are similarly proportioned in Tables B5 and B6. Other approaches would apportion more of the land use change to the vegetable oil and therefore the biofuel. For example, Fargione *et al*. 2008 apportioned 39% of the land use change from soybean biodiesel to the biofuel based on the market value of soybean oil and meal. Another possible approach might apportion 35% of land use change to soybean oil based on calorie content, recognizing that both oil and protein feed are high value agricultural products. A more formal modeling approach actually calculates the land use change that results from diverting a projected level of soybean oil according to partial equilibrium analysis, but formal models have their own uncertainties. Overall, we consider our approach more likely to underestimate land use change from soybean biodiesel than to overestimate it.

Our analysis estimates that the production of 1 billion L of US soy biodiesel requires an increase in cropland of 789,100 hectares around the world, with Argentina and Brazil as the major suppliers of soybeans and Indonesia and Malaysia as the major suppliers of palm oil. The large increase attributed to Argentina reflects its extensive processing technology and its large resulting share of soybean oil exports.[3]

New cropland results from the conversion of forest or grassland, releasing virtually all of the carbon in standing vegetation and much of the carbon in soil. The amount of the carbon release depends on the carbon content of the forest or grassland, which varies by region and ecosystem type. To estimate this carbon content, we worked previously with Dr. R.A. Houghton of the Woods Hole Research Center (Falmouth, MA) to estimate the proportion of new cropland in the 1990s that came out of different major ecosystem types, the carbon content of each, and the likely carbon emissions for each (Searchinger *et al*. 2008). This method generated a weighted average emission per converted acre for each major world agricultural region or country. On the assumption that future conversion would come proportionately from the same forest and grassland types as conversion in the 1990s, we assigned this weighted average emission to each hectare of conversion by country. (Table B6) The sum of these emissions, 340 million MT, represents the total emissions from land use change to produce 1 billion L of US soybean biodiesel, not including the associated oil meals. These emissions represent only those emissions from land use change that are likely to occur over a 30 year period.

We then incorporated these emissions for land use change into the lifecycle analysis for soy-based biodiesel in the GREET model (using its 2015 scenario). GREET compares the lifecycle emissions for soy biodiesel with the emissions from using regular and reformulated gasoline and conventional fossil-based diesel fuel. A hectare of soybeans will produce a new amount of biodiesel each year. To represent

[3] In the future, Brazil, which is the world's largest exporter of soybeans, is likely to increase its processing capacity and therefore export more soybean oil and more soybean meal, and Brazil may very well be the largest alternative supplier of soybean oil. However, we attribute the same emissions per converted acre both to Brazil and Argentina because both are in our Latin America region. Thus, this shift would not change our calculations, which may be more consistent with the large conversion expected in Brazil.

Table 1: Comparison of Biodiesel to Gasoline and Diesel With and Without Land use Change By Stage of Production and Use [Assuming No Demand Reduction or Price-Induced Yield Increase].

In grams of greenhouse gasses CO_2 equivalent per mile							
				Net Land Use Effects			
Source of Fuel	Making Feedstock	Refining Fuel	Vehicle Operation (Burning Fuel)	Feedstock Uptake from Atmosphere (GREET)	Land Use Change	Total GHGs	% Change in Net GHGs for Biodiesel vs. Diesel
Diesel	+18	+40	+246	0	—	+304	—
Biodiesel / (GREET)	+82	+81	+248	-272	—	+139	-54%
Biodiesel + Land Use Change							
Diverted Oil Replaced Solely by Soybean Oil	+82	+81	+248	-272	+656	+795	+161%
Diversion Replaced by Soybeans Only	+82	+81	+248	-272	+693	+832	+174%
Diverted Oil Replaced by Mix of Oils	+82	+81	+248	-272	+1,074	+1,213	+299%

the emissions from land use change, we amortized the total emissions over a 30 year period, *i.e.*, divided by 30, producing the emissions per liter used over that period. CO_2-equivalent emissions per liter are 0.0113 MT/L, or 11,345 grams (g)/L.[4] GREET presents emissions in the form of grams of emissions of greenhouse gasses (CO_2 equivalent) per mile driven. In this form, the results are presented in Table 1.

The result shows that emissions from land use change dominate the total emissions. For example, according to GREET, diesel from fossil fuels emits 304 g/mile and biodiesel emits 139 g/mile, but land use change emissions add 1,074 g/mile.[5]

Incorporating Demand Changes and Possible Price-Induced Yield Improvements

The above calculations assume that producers will replace all soybean oil diverted to biodiesel. In reality, that diversion will raise prices and depress demand. Determining the amount of depressed demand requires a model that would estimate the relative cost of increasing supply and the relative sensitivity of demand on a worldwide basis. In the absence of such an analysis, we assume that rising prices would decrease demand by 20%. If that were the case, the emissions from land use change would decline by 20% – 20% less land conversion would be required – but would still amount to 860 g/mile. It is worth emphasizing that while this decline in demand would lessen the increase in greenhouse gasses, there would be other social consequences.

Rising prices would also trigger efforts to improve yields. The analysis above assumes that these yield investments only balance out reliance on more marginal land. It is possible they could do more. For this sensitivity analysis we assume that higher soybean oil prices generated by biodiesel spur farmers to increase yields beyond those they would otherwise achieve sufficient to replace 20% of the diverted vegetable oil, and that would also decrease emissions from land use change by 20%. If both occurred, overall emissions from land use change would be 40% lower. At 645 g/mile for land use change, and 784 g/mile emissions in total, biodiesel would increase emissions compared to conventional diesel by 158% over 30 years (Table 2).

Alternative Scenarios

The above analysis assumes that the shift to biofuels results in reductions in US oil exports. For sensitivity purposes, we analyzed a scenario in which the biofuels instead result in a reduction in US exports of soybeans, and other countries make up the soybeans in response to their share of world soybean exports. In this scenario, the conversion is modestly lower at

[4] These are calculated by dividing the CO2-equivalent emissions from converting land for crops for 1 billion liters of biodiesel and further by 30 years to amortize the carbon change over the period in which it is likely to occur. For example, in the oil-only scenario with oil substitution, 340,351,788 MT/billion L/30 years is 0.01134506 MT/L.

[5] This calculation assumes that the emissions associated with producing the vegetable oils to replace soybean oil diverted to biofuels are the same as those involved in producing the soybean oil in the United States per unit of oil. These are emissions from tractors, fertilizer, and transportation. While this is a reasonable simplifying assumption, it is also relative unimportant given the dominance of the emissions from land use change.

Table 2: Comparison of Biodiesel to Gasoline and Diesel With and Without Land use Change By Stage of Production and Use [Assuming Demand Reductions and Price-Induced Yield Increases Replace 40% of Diverted Soybean Oil].

In grams of greenhouse gasses CO_2 equivalent per mile

Source of Fuel	Making Feedstock	Refining Fuel	Vehicle Operation (Burning Fuel)	Net Land Use Effects: Feedstock Uptake from Atmosphere (GREET)	Net Land Use Effects: Land Use Change	Total GHGs	% Change in Net GHGs for Biodiesel vs. Diesel
Diesel	+18	+40	+246	0	—	+304	—
Biodiesel / (GREET)	+82	+81	+248	-272	—	+139	-54%
Biodiesel + Land Use Change							
Diverted Oil Replaced Solely by Soybean Oil	+82	+81	+248	-272	+394	+533	+75%
Diversion Replaced by Soybeans Only	+82	+81	+248	-272	+416	+555	+83%
Diverted Oil Replaced by Mix of Oils	+82	+81	+248	-272	+645	+784	+158%

656,928 hectares because Brazil assumes the lion's share of increased production, and soybean yields in Brazil are exceptionally high. That results in lower greenhouse gas emissions for land use of 220 million MT, or emissions of 7,317 g/L. See Appendix Tables C1 through C4. That implies an increase in emissions compared to diesel fuel by 174% over 30 years (Table 1). Applying the assumptions of a total 40% reduction in land area needed because of reductions in demand for vegetable oil and price-induced increases in yield, biodiesel would increase emissions compared to conventional diesel by 83% (Table 2).

We also analyzed a scenario in which the United States responds to increased biodiesel production solely by reducing soybean oil exports, but they are replaced entirely by soybean oil produced by other exporters (Tables D1-D2). In that scenario, biodiesel increases emissions compared to conventional diesel by 161% (Table 1). These reductions are lower because virtually all replacement soybean oil comes from Latin America where soybean yields are significantly higher. If we assume the reductions in demand and further yield increases discussed above, greenhouse gas emissions would still increase by 75% (Table 2).

Finally, it is useful to hypothesize a scenario in which emissions per converted hectare would actually be half of our estimates. Even under those assumptions, and assuming the reductions in demand and the yield improvements reflected in Table 2, biodiesel would still increase greenhouse gas emissions compared to conventional biofuels. In the scenario that permits a range of vegetable oil replacements, the increase in greenhouse gas emissions over 30 years would still be 52%.

Conclusion

The actual market responses to an increase in biodiesel would be more complex than those estimated here. There would be more adjustments within countries as land shifts from one crop to another, and therefore more countries would increase production on cropland of some kind to supply the replacement crops. Even so, the ultimate determinant of land use change is that supply and demand must meet. More complex modeling would provide some alternative, potentially improved estimates of the precise levels of increased production in each country, but agricultural models also produce somewhat different results. But this analysis shows why the general world story should be relatively clear first because a small number of countries dominate the production of different oils, and second because soybean oil and palm oil dominate the overall vegetable oil production. Our analysis provides a useful range of estimates. Our results indicate that soybean biodiesel production, despite its high savings from a pure engineering perspective, dramatically increases greenhouse gas emissions compared to conventional diesel when factoring in emissions from land use change across a broad range of assumptions.

References

Argonne National Laboratory. *Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) Computer Model*. Argonne, IL: Argonne National Laboratory, Transportation Technology R&D Center, 2007. [Accessed May 5, 2007.] Documentation available at http://www.transportation.anl.gov/software/GREET/publications.html

Bradsher, Keith. "A New Global Food Quandary: Costly Fuel Means Costly Calories." *The New York Times*, January 19, 2008, p. 1A .

Farrell, Alexander E., Richard J. Plevin, Brian T. Turner, Andrew D. Jones, Michael O'Hare and Daniel M. Kammen. "Ethanol Can Contribute to Energy and Environmental Goals." *Science* 311(5760)(January 27, 2006): 506-508. [Accessed May 7, 2008.] Available from http://www.sciencemag.org/cgi/content/full/311/5760/506

Fargione, Joseph, Jason Hill, David Tilman, Stephen Polasky, Peter Hawthorne. "Land Clearing and the Biofuel Carbon Debt." *Science* 319(1235)(February 29, 2008) (supporting online materials). [Accessed December 18, 2008.] Available from http://www.sciencemag.org/cgi/content/full/319/5867/1235

Food and Agricultural Policy Research Institute. *FAPRI 2007 U.S. and World Agricultural Outlook*. FAPRI Staff Report 07-FSR 1. Ames, IA: Iowa State University and University of Missouri-Columbia, Food and Agricultural Policy Research Institute, January 2007. [Accessed May 7, 2008.] Available from http://www.fapri.iastate.edu/Outlook2007/

Searchinger, Timothy, Ralph Heimlich, R.A. Houghton, Fengxia Dong, Amani Elobeid, Jacinto Fabiosa, Simla Tokgoz, Dermot Hayes and Tun-Hsiang Yu. "Use of US Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change." *Science* 319(5867)(February 29, 2008): 1238-1240. [Accessed May 7, 2008, 2008.] Available from http://www.sciencemag.org/cgi/content/full/319/5867/1238

Appendix A: US Soybean Production and Disposal

Table A1: US Soybean Production and Disposal, Projected for 2016/17 Baseline.

FAPRI US Baseline Data 2016/17 (Thousand MT)	
Production	85,065
Crush	54,874
Seed, Residual	5,003
Ending Stocks	11,617
Domestic Use	71,494
Meal	43,580
Oil	10,434
Area Harvested (Thousand Hectares)	27,929
FAPRI US Baseline Net Exports 2016/17 (Thousand MT)	
Soybeans	24,987
Meal	7,980
Oil	1,337

Source: Food and Agricultural Policy Research Institute (2007).

Appendix B: Tables for Main Scenario – US Soybean Oil Diverted to Biodiesel and Replaced by a Mix of Vegetable Oils

Table B1: Reduction in US Soybean Oil Exports in Response to Diversion of US Soybean Oil to Provide 1 Billion Liters of Biodiesel.

			1998-2007 Average		Export Reduction
Mexico	Soybean Oil	MT	79,587	13.8%	251.5
China, Peoples Republic of	Soybean Oil	MT	66,220	11.5%	209.2
Canada	Soybean Oil	MT	49,096	8.5%	155.1
Korea, Republic of	Soybean Oil	MT	40,990	7.1%	129.5
India	Soybean Oil	MT	28,280	4.9%	89.4
Hong Kong	Soybean Oil	MT	25,695	4.4%	81.2
Peru	Soybean Oil	MT	25,161	4.4%	79.5
Egypt	Soybean Oil	MT	21,842	3.8%	69.0
Morocco	Soybean Oil	MT	18,732	3.2%	59.2
Cuba	Soybean Oil	MT	18,586	3.2%	58.7
Rest of the world	Soybean Oil	MT			642.8
Total	Soybean Oil	MT	577,616	100.0%	1,825.1

Table B2: Mix of Oils to Substitute for Displaced US Soybean Oil Exports and Based on Each Country's Present Mix of Vegetable Oils.

Country	Peanut	Palm	Rapeseed	Soybean	Sunflower	Total oils
	Thousand MT					
Mexico	15.9	75.7	22.6	128.0	9.2	251.5
China	25.3	34.5	17.0	128.5	4.0	209.2
Canada	19.1	0.0	110.7	21.6	3.7	155.1
Korea, Republic of	4.4	20.0	2.3	102.5	0.2	129.5
Hong Kong (same as China)	10.8	14.7	7.2	54.9	1.7	89.4
India	11.7	33.4	12.2	21.9	2.1	81.2
Peru	0.8	16.9	0.0	60.8	0.9	79.5
Egypt	5.8	5.3	0.0	40.6	17.3	69.0
Morocco	1.5	0.2	1.2	52.8	3.5	59.2
Cuba	1.3	0.0	0.0	57.2	0.2	58.7
United States	0.0	0.0	0.0	0.0	0.0	0.0
ROW	45.2	95.4	75.9	405.0	21.3	642.8
Total	142.1	296.1	249.2	1,073.7	64.0	1,825.1

Source: FAO data on oil consumption in grams/capita/day at http://faostat.fao.org/default.aspx applied to decrease in soybean oil exports.

Table B3: US Soybean Oil Export and Consumption Replacements by Major Vegetable Oil Exporters.

Country	Soybean	Palm	Rapeseed	Peanut	Sunflower	Total Oils
	Thousand MT					
Argentina	669	0	0	59	22	749
Brazil	287	0	0	0	0	287
Canada	0	0	200	0	0	200
Indonesia	0	170	0	0	0	170
Malaysia	0	127	0	0	0	127
CIS	0	0	45	0	39	84
ROW	0	0	0	72	0	72
China	0	0	0	9	0	9
Bulgaria and Romania	2	0	2	0	3	6
Australia	0	0	3	0	0	3
India	0	0	0	3	0	3
United States	116	0	0	0	1	117
Total Net exports	1,074	296	249	142	64	1,825

Note: Analytically, the "increase" in exports from the United States represents a smaller reduction in exports, but is separately represented here to represent the increased production from the United States to maintain some portion of the export market that would otherwise be lost due to the diversion for biodiesel.

Table B4: Increased Crop Area, Feedstock for Oils by Exporting Country – Total Area Needed to Produce Crop.

	Soybean	Palm	Rapeseed	Peanut	Sunflower	Total
	Thousand Hectares					
Argentina	1,146.9			50.1	28.3	1,225.3
Brazil	515.3					515.3
Canada	0.0		254.3			254.3
Indonesia		95.0			95.0	
Malaysia		60.5				60.5
CIS	0.0		76.7		69.5	146.2
ROW	0.0		0.0	192.4	0.0	192.4
China	0.0		0.0	8.6	0.0	8.6
Bulgaria and Romania	4.0		2.6		4.0	10.5
Australia			6.1			6.1
India	0.0		0.0	7.8		7.8
United States	200.6	0.0	0.0	0.0	1.5	202.1
World	1,666.2	155.5	339.7	258.9	101.8	2,522.2

Table B5: Increased Crop Area, Feedstock for Oils – Area Apportioned for Oil Only.

	Soybean	Palm	Rapeseed	Peanut	Sunflower	Total
	Thousand Hectares					
Argentina	223.9	0.0	0.0	21.6	11.4	256.9
Brazil	99.1	0.0	0.0	0.0	0.0	99.1
Canada	0.0	0.0	106.8	0.0	0.0	106.8
Indonesia	0.0	95.0	0.0	0.0	0.0	95.0
Malaysia	0.0	60.5	0.0	0.0	0.0	60.5
CIS	0.0	0.0	29.8	0.0	28.6	58.4
ROW	0.0	0.0	0.0	62.9	0.0	62.9
China	0.0	0.0	0.0	2.7	0.0	2.7
Bulgaria and Romania	0.7	0.0	1.0	0.0	1.6	3.3
Australia	0.0	0.0	2.4	0.0	0.0	2.4
India	0.0	0.0	0.0	2.6	0.0	2.6
United States	38.1	0.0	0.0	0.0	0.3	38.4
World	361.9	155.5	140.1	89.8	41.8	789.1

Table B6: Increase in Emissions by Country or Region for Scenario in Which Vegetable Oils Are Replaced by a Mix of Oils.

Region	Area Change, Hectares	CO_2 Equivalent per Hectare MT/Hectare	Total Emissions, CO_2 Equivalent, MT
Canada	106,802	311.1913628	33,236,011
Africa	0		0
Europe	3,338	262.2082968	875,318
Former Soviet Union	58,397	196.8970315	11,498,124
Latin America	355,991	336.9466343	119,949,903
North Africa and Middle East	0	0	0
Developed Pacific	2,439	232.3691887	566,840
China/India/Pakistan	5,272	199.0975	1,049,640
Southeast Asia	155,549	1018.57157	158,437,974
United States	38,423	383.5765619	14,737,977
Rest of the World	62,930	0	0
Total	789,142		340,351,788

Appendix C: Tables for Scenario in Which United States Reduced Soybean Exports, which are Replaced by Soybean Exports from Other Countries.

Table C1: Reduction in US Soybean Oil Exports to Importing Countries.

			1998-2007 Average		Export Reduction
Mexico	Soybean Oil	MT	79,587	13.8%	251.5
China, Peoples Republic of	Soybean Oil	MT	66,220	11.5%	209.2
Canada	Soybean Oil	MT	49,096	8.5%	155.1
Korea, Republic of	Soybean Oil	MT	40,990	7.1%	129.5
India	Soybean Oil	MT	28,280	4.9%	89.4
Hong Kong	Soybean Oil	MT	25,695	4.4%	81.2
Peru	Soybean Oil	MT	25,161	4.4%	79.5
Egypt	Soybean Oil	MT	21,842	3.8%	69.0
Morocco	Soybean Oil	MT	18,732	3.2%	59.2
Cuba	Soybean Oil	MT	18,586	3.2%	58.7
Rest of the World					642.8
Total	Soybean Oil	MT	577,616	100.0%	1,825

Table C2: Increased soybean exports by other exporters, 2016/17.

Net Soybean Exporters	Baseline Exports	Production of Displaced US Exports	New Soybean Production	New Soybean Area	New Soybean Area (Oil Only)
	(Thousand MT)			(Thousand Hectares)	
Argentina	7,878	1,294	1,294	433	85
Brazil	50,529	8,297	8,297	2,863	551
Bulgaria and Romania	46	8	8	3	1
Canada	1,092	179	179	62	10
CIS	433	71	71	61	11
India	5	1	1	1	0
United States	24,987				
Total Net Exports	84,970	9,850	9,850	3,423	657

Table C3: Greenhouse Gas Emissions from Cropland Conversion to Replace US Soybean Exports.

Region	Area Change, Hectares	CO_2 Equivalent per Hectare MT/Hectare	Total Emissions, CO_2 Equivalent, MT
Canada	0		0
Africa	10,385	311.2	3,231,741
Europe	552	262.2	144,790
Former Soviet Union	10,677	196.9	2,102,179
Latin America	635,165	336.9	214,016,734
North Africa and Middle East	0		0
Developed Pacific	0		0
China/India/Pakistan	149	199.1	29,738
Southeast Asia	0		0
Rest of the World	0		0
Total	656,928		219,525,183

Note: Emission rates from deforestation, except rates in Europe and the Former Soviet Union are from afforestation prevented on cropland that would otherwise be retired.

Appendix D: Tables for Replacement of Diverted Soybean Oil Solely by Soybean Oil from other Countries.

See Table B1 for reductions in US soybean oil exports.

Table D1: Increased Soybean Oil Exports by Other Oil Exporters, 2016/17.

Net Soybean Oil Exporters	Baseline Exports	Displaced US Exports	New Soybean Meal Production	New Soybean Production	New Soybean Area	New Soybean Area (Oil Only)
	Thousand MT				Thousand Hectares	
Argentina	7,711	1,274	5,253	6,527	2,186	427
Brazil	3,313	547	2,299	2,846	982	189
Bulgaria and Romania	20	3	15	19	8	1
United States	1,337					
Total Net Exports	12,381	1,825	7,567	9,392	3,175	617

Note: Because only the soybean oil replaces displaced US exports, only the crop area supporting the oil production should be counted against US soy biodiesel production. This amounts to only 617 thousand hectares (about 19 percent of the total).

Table D2: Greenhouse Gas Emissions from Cropland Conversion to Replace US Soybean Oil Exports Entirely by Soybean Oil.

Region	Area Change, Hectares	CO_2 Equivalent per Hectare MT/Hectare	Total Emissions, CO_2 Equivalent, MT
Canada	0		0
Africa	0		0
Europe	1,358	262.2	355,957
Former Soviet Union	0		0
Latin America	615,566	336.9	207,412,893
North Africa and Middle East	0		0
Developed Pacific	0		0
China/India/Pakistan	0		0
Southeast Asia	0		0
United States	0		0
Rest of the World	0		0
Total	616,924		207,768,850