Assessing induced economic and environmental impacts of biofuels and their consequential life-cycle analyses in a computable general equilibrium framework: An exercise with GTAP-BIO model

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1. Introduction

Since the surge in biofuel production in the late 2000s, various efforts have been made to study the economic and environmental impacts of biofuel production and policies. These efforts have addressed various related topics including but not limited to: 1) Techno-Economic Analysis (TEA) and feasibility studies of alternative biofuel pathways; 2) supply chain and Life-Cycle Analysis (LCA) of alternative biofuel technologies; 3) assessing the long-run and short-run effects of biofuel production and policy on welfare, agricultural activities, commodity markets, and energy markets at local, national, and global scales; and 4) evaluating the Induced Land Use Changes (ILUC) due to biofuels and their corresponding greenhouse gas (GHG) emissions. While the existing literature has frequently addressed these topics, limited attempts have been made to study several other effects that biofuels may generate. Some of these effects include the following: induced changes in global GHG emissions (CO_2 and non-CO_2); market-mediated impacts on the livestock sector; market-mediated effects on markets of fossil fuels; and impacts on food consumption and its composition. As well documented in the National Academies of Sciences, Engineering, and Medicine (NASEM, 2022) report, more research is needed to identify and quantify these effects. In particular, the NASEM report has noted that more consequential analyses are required to assess the direct and indirect economic and environmental effects of biofuel production and policies.

This paper fills the existing knowledge gap and develops consequential analyses to better quantify the economic and environmental impacts of biofuels produced in the US. It uses a well-known Computable General Equilibrium (CGE) model to quantify the following impacts of ethanol and soybean oil biodiesel produced in the US: 1) induced land use GHG emissions; 2) induced changes in energy markets; 3) changes in CO_2 and non-CO_2 GHG emissions due to changes in consumption, production, and trade of all goods and services at the global scale from a Life-Cycle assessment approach (covering emission Scopes 1,2, and 3); 4) induced changes in primary livestock and livestock products at the global scale by region; and 5) induced changes in crop production.

This paper provides new assessments that have not been made in the past. Following the NASEM recommendations, it sheds light on the under-studied global impacts of biofuels production. It helps to better quantify and understand some unexamined effects of biofuels and enhances the policy decisions regarding their production. Some findings of this research have already been used by the US Environmental Protection Agency (EPA, 2023) to inform policy makers regarding the impacts of biofuels.

2. Methodology and modeling framework

Given the goals and scope of this paper, we used a global CGE model (GTAP-BIO) that traces the production, consumption, and trade of all goods and services supplied across the world by region. This model has been frequently improved and used to evaluate induced land use emissions due to biofuels (a few examples are: Taheripour et al., 2010; Hertel et al., 2010, Zhao et al., 2021). The model was built based on the GTAP-E model developed by Burniaux and Truong (2002) and McDougall and Golub (2007). Taheripour et al. (2017) have introduced the latest version of the

GTAP-BIO model and its background. The GTAP-BIO modeling structure is presented in Figure 1. Unlike the standard GTAP model, this model could explicitly trace the production, consumption and trade of biofuels and their by-products. It represents agricultural and forestry activities among all other economic sectors. It is the comprehensive nature of GTAP models that allows us to determine the effects that changes in biofuels have on other sectors. First, because it tracks the interaction between products and services and also because it links products with their inputs. Such inputs include factor endowments, for which an allotment is typically fixed and its use is competitive. Furthermore, the model tracks trade flows, which is how this type of model determines how US policy can affect other countries. In addition, it evaluates induced land use changes due to changes in demands for food, feed, biofuels, and forest products by region and 18 Agro-Ecological Zones.

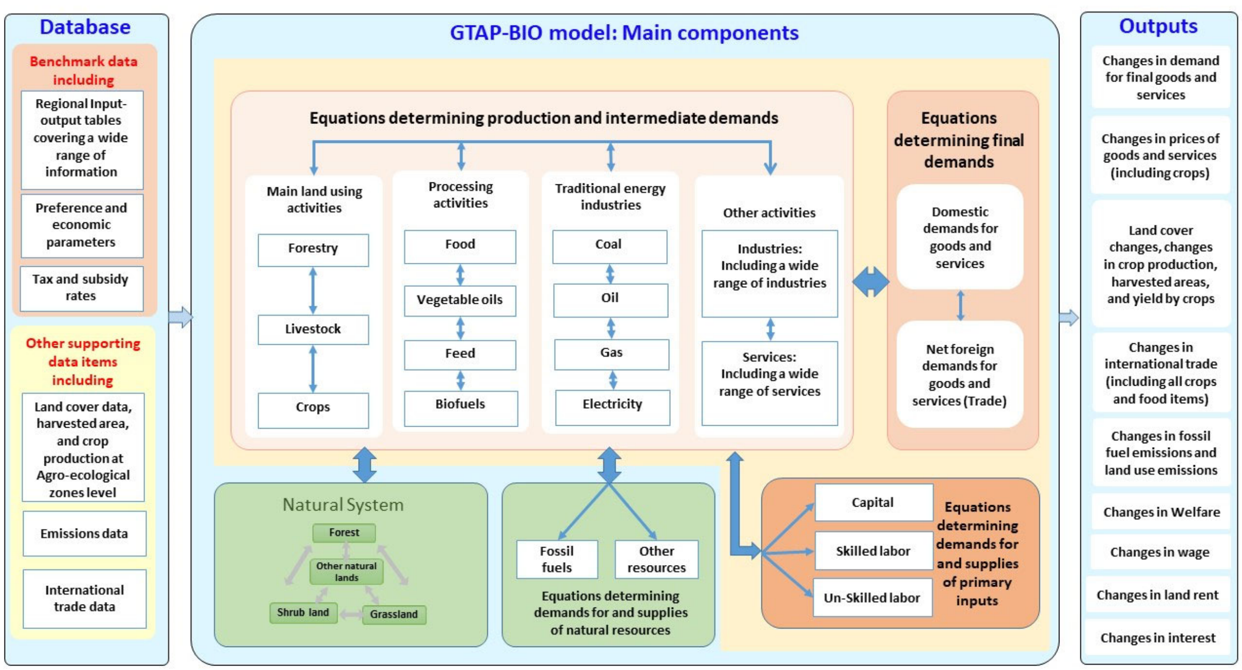

Figure 1. Schematic of GTAP-BIO Model (prepared based on Taheripour et al. 2019)

The GTAP-BIO model and its data base usually divide the whole world into 19 countries/regions. Figure 2 presents these regions.

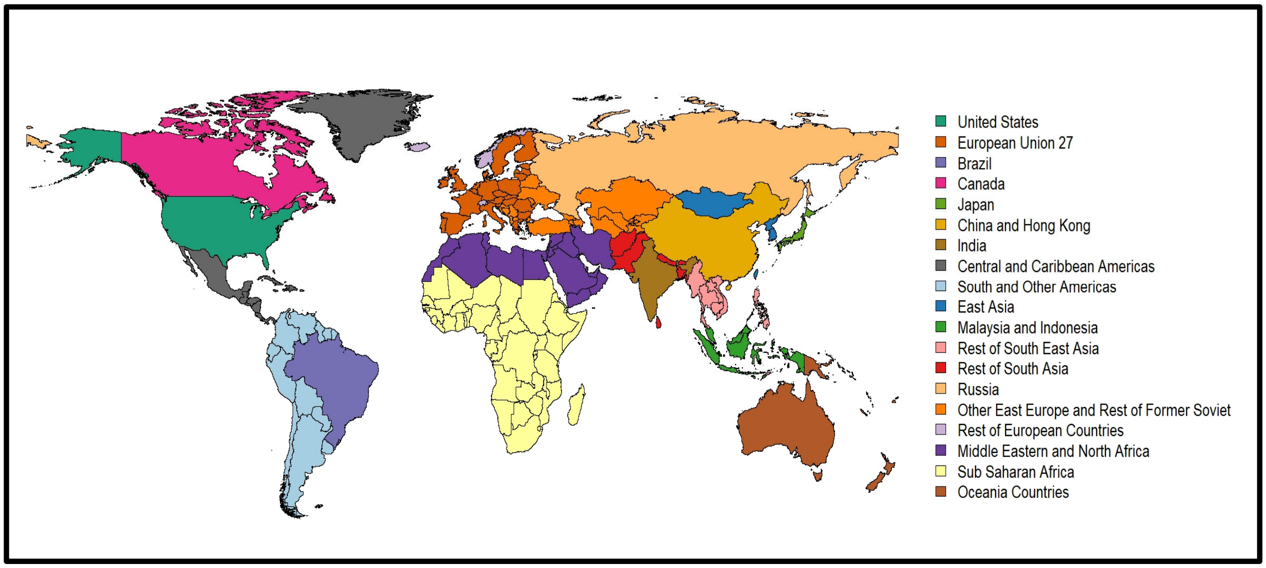

Figure 2. GTAP-BIO aggregated geographical regions

Since the standard GTAP data base does not explicitly represent biofuel activities, a benchmark data base has been developed for this model. The first version of this data base was developed by Taheripour et al. (2008) by introducing ethanol produced from grains and sugarcane and biodiesel produced from vegetable oils into the GTAP data base version 6 with the reference year of 2001. In that year, except Brazil, only a few countries were producing limited amounts of biofuels. Then, Taheripour and Tyner (2011) introduced grain ethanol, sugarcane ethanol and biodiesel produced from vegetable oils into the GTAP data base version 7 with the reference year of 2004. Given the impacts of biofuel industries on the livestock and feed industries, the new GTAP-BIO data base distinguished between the food and feed industries as well. Two hypothetical advanced cellulosic biofuels (corn stover ethanol and miscanthus ethanol) were also introduced to this data base.

The next version of the GTAP-BIO data base was developed using the version 9 of the standard GTAP data base for the reference year of 2011 including more data refinements to better represent interactions between crop sectors, livestock industries, and biofuel sectors as described by Taheripour et al. (2016b). The new data base considered additional splits of economic activities including: 1) split of oilseeds to soybeans, rapeseed (canola), palm fruit, and other oilseeds; 2) split of vegetable oils to soy oil, rapeseed (canola) oil, palm oil and other vegetable oils and fats; 3) split of outputs of the vegetable oil sectors into meals and oils; 4) split of coarse grains into sorghum and other coarse grains; 5) distinguishing between food and feed products and industries; 6) introducing a new sector to blend biofuels with conventional petroleum products; 7) introducing marginal land (known as cropland pasture) into the rest of crops to allow return of this type of land to crop production as frequently occurs in the real world; and 8) including cellulosic ethanol pathways.

It should be noted that in 2011 many countries were producing the first generation of biofuels including grain ethanol (corn or wheat ethanol), ethanol produced from sugar crops, and biodiesel produced from soy oil, rapeseed oil, palm oil, and other types of vegetable oils and fats. These biofuels were introduced in the 2011 GTAP-BIO data base. In addition, several hypothetical advanced cellulosic biofuels were also introduced to this data base.

The latest version of the GTAP-BIO data base represents the reference year of 2014 and it has been developed using the standard GTAP data base version 10a. To develop this data base several changes were made in the standard GTAP data base as presented in Figure 3.

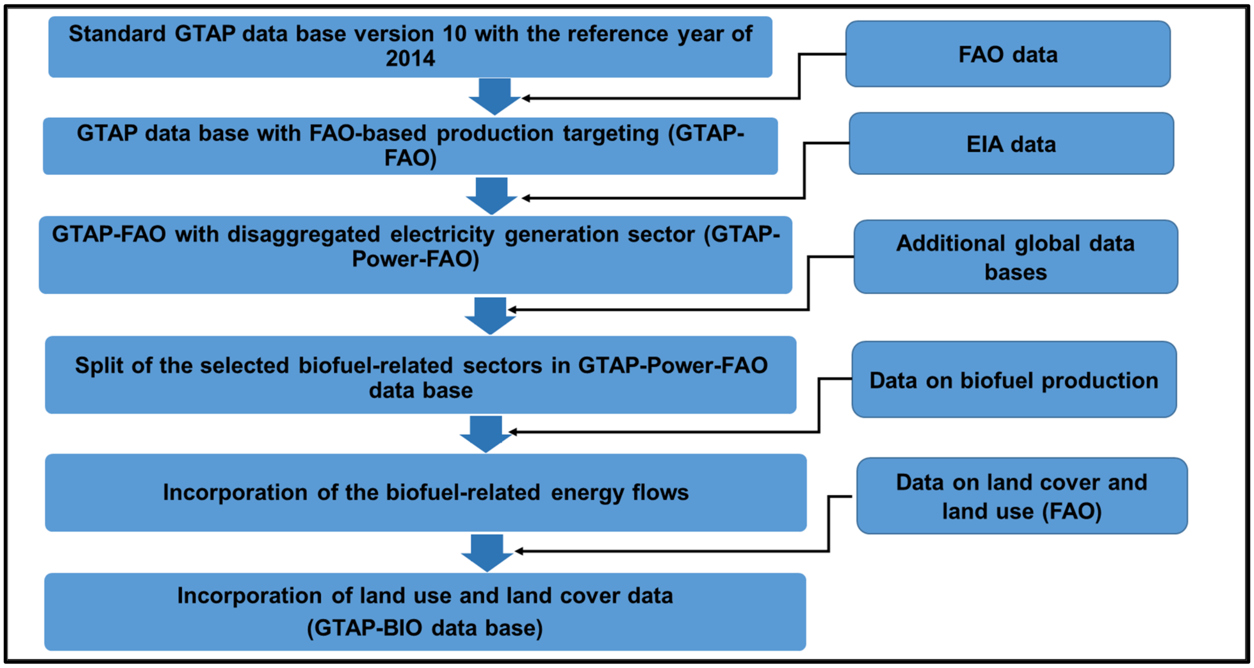

Figure 3. Collected data and implemented steps in developing the 2014 GTAP data base

Following Chepeliev (2020), the model is improved to trace changes in CO_2 and non-CO_2 GHG emissions due to changes in economic activities. Emissions are reported for three types of non-CO_2 GHGs – methane (CH_4), nitrous oxide (N_2O) and the group of fluorinated gases (F-gases). In addition, CO_2 emissions from non-fossil fuel combustion activities, such as the production of cement and fertilizers, are reported in the model. The FAOSTAT dataset is used for sourcing agricultural GHG emissions, while the EDGAR database is used to source non-agricultural GHG emissions. Each emission flow in the model is associated with one of the four sets of emission drivers: output by industries, endowment by industries, input use by industries and consumption by households. As a result, the developed model covers CO_2 emissions from fossil fuel combustion, CO_2 emissions from industrial processes, methane, nitrous oxide and a group of fluorinated gases.

Several new modules and data items are added to the model to trace changes in livestock and processed livestock, and food products.

3. Examined experiments

Three experiments were conducted in this paper. The first experiment isolates the global consequential economic and environmental effects of producing one billion gallons of additional corn ethanol in the US from all other drives that might affect the global economy. The second experiment repeats the same analyses for soybean oil biodiesel produced in the US. The third experiment evaluates the joint effects of an increase in corn ethanol by one billion gallons and an increase in soy biodiesel by 1 billion gallons. Henceforth, we call these experiments as: ***Experiment I***, **Experiment II***,* and ***Experiment III***.

4. Results

The experiments described above provide a wide range of numerical assessments. The paper provides the results for the following key areas:

4.1. ILUC emissions and the corresponding land use changes

The ILUC emissions are presented in Figure 4. As shown in this figure, the projected ILUC emissions for corn ethanol, soy biodiesel, and their joint production are about 5.6 gCO2e/MJ, 9.1 gCO2e/MJ, and 8.2 gCO2e/MJ. This means that the joint production of these two biofuels generates a larger ILUC value than their average, which is 7.4 gCO2e/MJ. This is because producing two biofules jointly demands more resources, including land. The projected ILUC emissions for corn ethanol and soybean biodiesel obtained from the new 2014 GTAP-BIO data base (results of experiments I and II are smaller than their corresponding numbers obtained from the 2011 GTAP-BIO data (12 gCO2e/MJ for corn ethanol and 18.3 gCO2e/MJ for soy biodiesel) reported in Taheripour et al. (2017). Among multiple factors that could explain these reductions, three key factors are: (1) the GTAP-BIO 2014 data base represents marginal land for all regions across the world, while the 2011 GTAP-BIO data base only represents marginal land for three regions (US, Brazil, and Canada); (2) crop yields are significantly higher in 2014 compared to 2011; and (3) the 2014 data base represents a larger area of crop production and more uses of crops that lead to more market mediated respoces across the world.

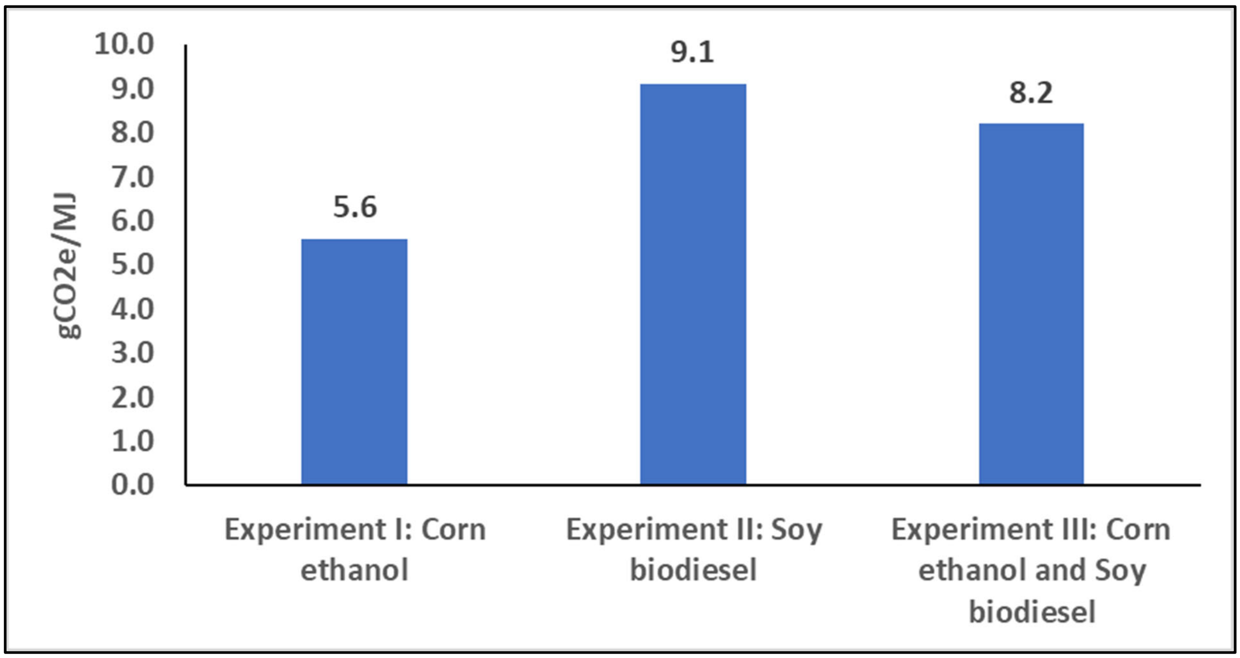

Figure 4. ILUC emissions for examined experiments

Table 1 summarizes the global land use changes for each examined experiment. The expansion in corn ethanol by 1 billion gallons increases the global harvested area by 156.6 thousand hectares. The corresponding number for the case of soy biodiesel is 175.3 thousand hectares. The joint production of corn ethanol and soy biodiesel increases the global harvested area by 331.4 thousand hectares. In each of these cases, the expansion in harvested area largely occurs outside the US. As shown in Table 1, across the examined cases the expansions in harvested areas are mainly expected to come from reductions in marginal lands (cropland pasture, or unused land). Multiple cropping also provides more harvested area without expansion in cropland. Conversions of forest and pasture land to cropland also satisfy expansions in harvested areas across the world for the examined experiments.

Table 1. Induced land use changes for examined experiments (1000 hectares)

Description	Experiment I: Corn ethanol			Experiment II: Soy biodiesel			Experiment III: Corn ethanol and Soy biodiesel		
	USA	Non-USA	Total	USA	Non-USA	Total	USA	Non-USA	Total
Change in H area of crops	43.5	112.6	156.2	34.5	140.7	175.3	77.5	253.7	331.3
Change in cropland pasture	-32.7	-60.3	-93.0	-24.5	-75.2	-99.7	-56.9	-135.7	-192.5
Change in unused land	-6.9	-13.9	-20.8	-6.4	-15.1	-21.6	-13.3	-29.1	-42.3
Change in multiple cropping	-1.7	-6.5	-8.2	-1.6	-7.1	-8.7	-3.3	-13.6	-16.9
Change in forest	0.6	-8.4	-7.8	-2.8	-1.2	-4.0	-2.2	-9.6	-11.8
Change in pasture	-2.8	-23.5	-26.3	0.8	-42.0	-41.1	-2.0	-65.7	-67.7

4.2. Impacts of biofuel production on GHG emissions excluding ILUC emissions

In general, biofuel production/consumption displaces the use of fossil fuels and that could lead to savings in GHG emissions. However, the production of biofuels also generates GHG emissions. In addition, more biofuels may generate rebound effects in energy consumption. Furthermore, biofuel production may affect many other economic activities and those changes could lead to changes in GHG emissions around the world. Therefore, from a lifecycle assessment point of view (covering all three emission scopes), it is important to assess the extent to which biofuels may generate GHG emissions. This is a key analysis that could help to better assess the environmental effects of biofuel production. Figure 5 summarizes the impacts of increases in corn ethanol and soy biodiesel (each by 1 billion gallons) and their joint production on CO_2 and non-CO_2 emissions at the global scale, excluding the land use emissions. As shown in this figure, under the examined experiments, GHG emissions (CO_2 and non-CO_2 emissions) decline, except for the expansion in corn ethanol that increases non-CO_2 emissions by a small quantity of 0.085 million metric tons of CO_2 eq.

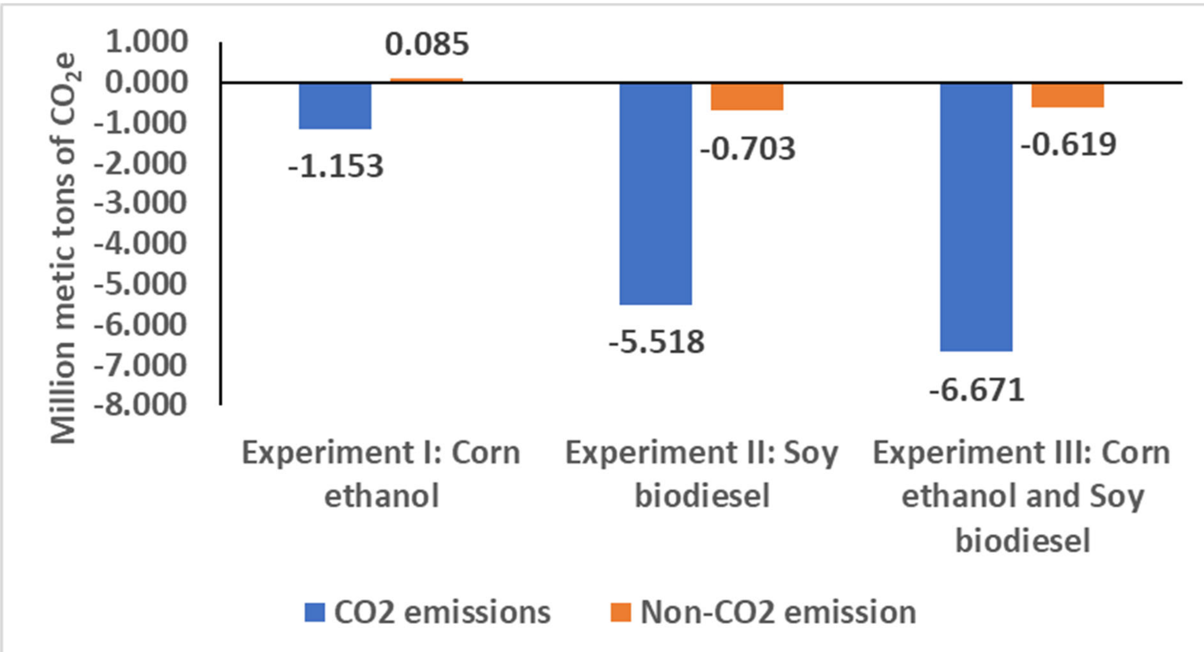

Figure 5. Changes in CO_2 and non-CO_2 emissions for examined experiments

Table 2 shows changes in the elements of GHG emissions including: CO_2 from fossil fuels combustion, N_2O, CH_4, F-gases, and non-combustion CO_2 emissions. From this table we could make the following inferences:

- Across the examined experiments, all emission changes are negative for the US, except for N_2O which shows an increase. This could confirm savings in emissions (largely CO_2) due to the substitution between fossil fuels and biofuels.

- Across the examined experiments, all emission changes are positive for the non-US, except for CH_4 which shows negative changes. This could confirm the presence of some rebound effects in the consumption of fossil fuels outside the US.
- In general biofuel production in the US generates savings in GHG emissions at the global level.

In conclusion, ignoring ILUC emissions, in general producing corn ethanol, soy biodiesel, and their mix leads to savings in CO_2 and non-CO_2 emissions at the global scale.

Table 2. Changes in GHG emissions for examined experiments (Million metric tons of CO_2e)

Description	Experiment I: Corn ethanol			Experiment II: Soy biodiesel			Experiment III: Corn ethanol and Soy biodiesel		
	USA	Non-USA	Total	USA	Non-USA	Total	USA	Non-USA	Total
Combustion CO_2	-1.705	0.552	-1.153	-6.853	1.336	-5.518	-8.560	1.889	-6.671
N_2O	0.290	0.120	0.410	0.087	0.043	0.130	0.375	0.164	0.539
CH_4	-0.210	-0.070	-0.280	-0.303	-0.415	-0.717	-0.513	-0.485	-0.998
F-gases	-0.010	0.011	0.001	-0.012	0.025	0.014	-0.022	0.037	0.015
Non-combustion CO_2	-0.106	0.061	-0.045	-0.256	0.126	-0.130	-0.362	0.187	-0.175
Total	-1.742	0.674	-1.068	-7.337	1.116	-6.221	-9.082	1.792	-7.290

4.3. *Overall carbon intensities*

Figure 6 represents the overall carbon intensities across the examined experiments and their components. The carbon intensities (sum of all GHG emissions including ILUC emissions) are -7.5 gCO2e/MJ, -40.3 gCO2e/MJ, and -27 gCO2e/MJ under experiments I, II, and III. These results suggest that biofuels provide savings in GHG emissions including CO_2, non-CO_2 and ILUC emissions.

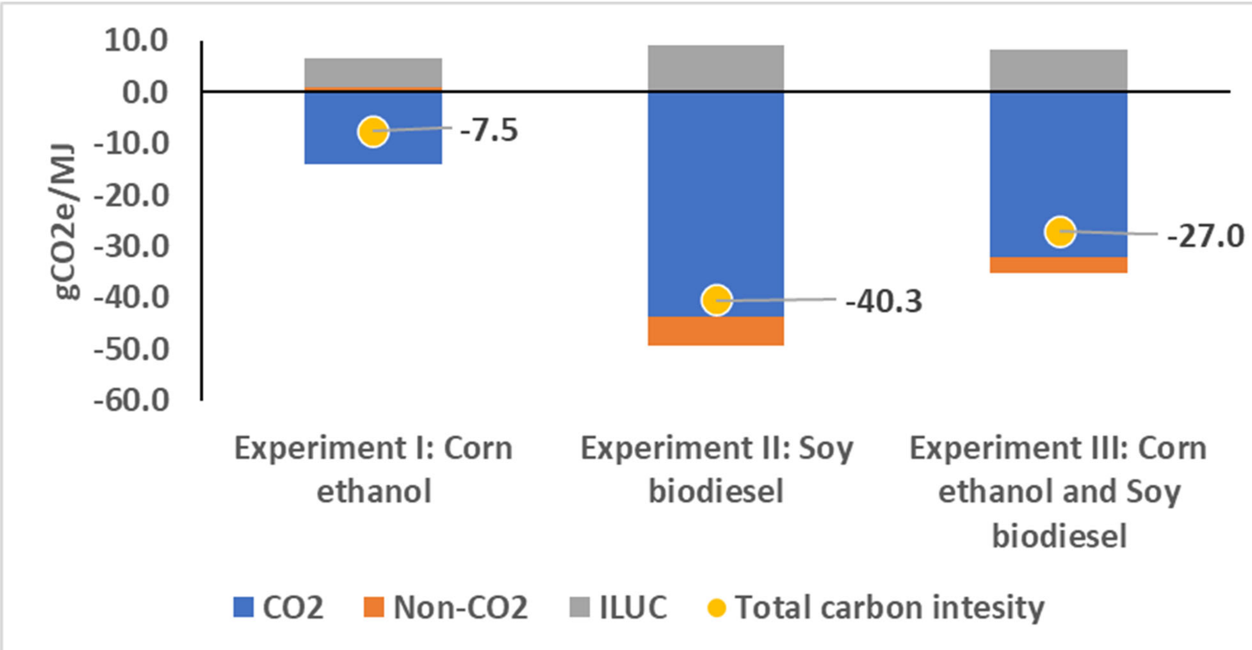

Figure 6. Carbon intensities of corn ethanol, soy-biodiesels, and their mix

4.4. *Trade effects*

Producing more biofuels could affect the US commodity trade. The Panel A of Figure 7, shows percent changes in the US commodity exports under the examined experiments. Overall, the results show reductions in exports of wheat, corn, other coarse grains, and soybeans with increases in exports of other oilseeds and other crops. The reduction in US exports stimulates other countries to expand their exports as shown in the Panel B of Figure 7. In general, figure 7 shows that the percent changes in exports are relatively small.

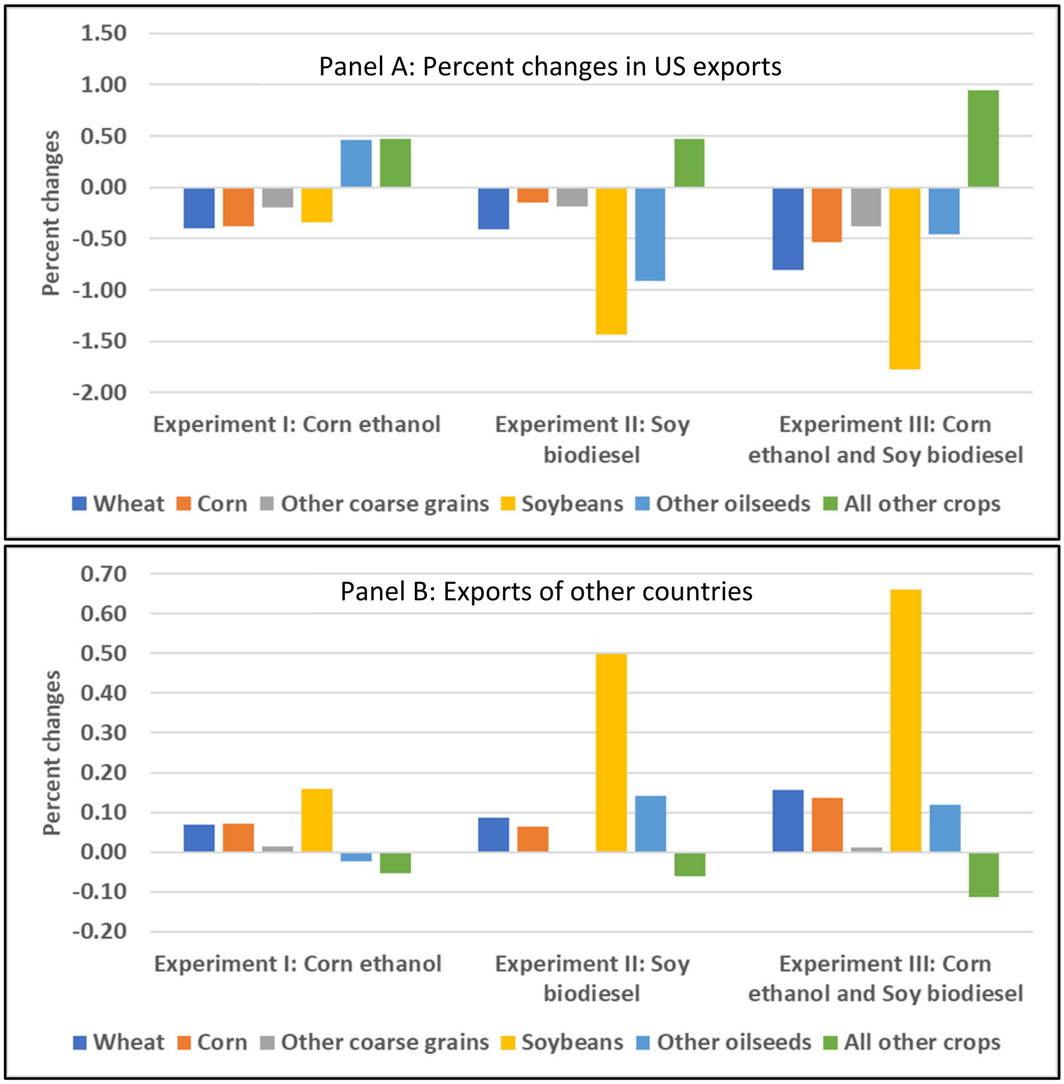

Figure 7. Change in commodity exports under the examined experiments

Table 3 shows changes in quantities of exports (in 1000 metric tons), which allows us to better understand the magnitude of the projected changes. Production of an additional one billion gallons of corn ethanol leads to a reduction in US corn exports by 190.6 thousand metric tons. On the other hand, additional production of 1 billion gallons of soy biodiesel leads to a reduction in US soy exports by 711.2 thousand metric tons. If both biofuels are produced jointly, the reductions in the US corn and soybeans are expected to be 266.8 thousand metric tons and 880.1 thousand metric tons respectively.

Table 3. Changes in crop exports for examined experiments (1000 metric tons).

Description	US exports			Non-US exports		
	Exp. I: Corn ethanol	Exp. II: Soy biodiesel	Exp. III: Corn ethanol and Soy biodiesel	Exp. I: Corn ethanol	Exp. II: Soy biodiesel	Exp. III: Corn ethanol and Soy biodiesel
Wheat	-102.5	-104.1	-206.2	103.4	127.6	231.3
Corn	-190.6	-75.2	-266.8	65.1	58.7	124.4
Other coarse grains	-14.8	-14.1	-29.0	6.2	-1.5	4.7
Soybeans	-167.5	-711.2	-880.1	109.8	343.1	455.3
Other oilseeds	2.6	-5.2	-2.6	-7.9	47.1	39.5
All other crops	68.8	68.4	136.9	-86.8	-98.6	-185.3

5. Conclusions

The results of this paper suggest that other factors being equal, expansions in the corn and soybean oil biodiesel produced in the US could reduce the CO_2 and non-CO_2 GHG emissions, including induced land use emissions, at the global scale. However, the effects vary across regions, types of emissions, types of biofuels, and economic sectors. The trade effects are usually very limited and only affect selected crops that the US economy exports to other countries (e.g., corn and soybeans).

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