Title: Regulating Indirect Land Use Change due to Biofuels: Is it Worth it?

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Summary: Efforts to reduce the indirect land use change (ILUC) related carbon emissions caused by biofuels has led to inclusion of an ILUC factor as a part of the carbon intensity of biofuels in a Low Carbon Fuel Standard (LCFS). While previous research has provided varying estimates of this ILUC factor, there has been no research examining the economic effects for the US and additional carbon savings globally from including an ILUC factor in implementing a LCFS. Using an integrated modeling framework we found that inclusion of an ILUC factor in a national LCFS led to additional abatement of cumulative emissions over 2007-2027 by 1.3% to 2.6% (0.6-1.1 Billion Mega-grams Carbon-dioxide-equivalent or B Mg CO_2e) compared to those without an ILUC factor, depending on the ILUC factors utilized. The welfare cost to the US of this additional abatement ranged from \$61 to \$187 Mg CO_2e^{-1} and was substantially greater than the monetary value of damages from carbon emissions (social cost of carbon) of \$50 Mg CO_2e^{-1}.

Main Text: Low carbon fuel policies at the federal and state level in the US such as the Renewable Fuel Standard (RFS) and the Low Carbon Fuel Standard (LCFS) in California seek to reduce dependence on fossil fuels and carbon emissions by inducing a switch towards biofuels. The RFS sets a quantity mandate for different types of biofuels that differ in their carbon intensity relative to gasoline. The RFS is implemented as a mandate to blend a certain share of biofuels with gasoline annually since 2007. On the other hand, a LCFS sets a target for the percentage reduction in the average carbon intensity of transportation fuel below a baseline level and provides blenders the flexibility to select the mix and quantities of different biofuels to meet the average fuel carbon intensity standard.

The production of biofuels has raised concerns about their competition for land with food crops resulting in higher global crop prices[1,2] that lead to indirect land use change (ILUC) globally by creating incentives for the conversion of non-cropland to crop production and releasing carbon stored in soils and vegetation[3]. Studies differ in their estimate of the extent to which biofuels have affected food crop prices with many studies estimating these to be 14% to 35% higher than in the baseline depending on the specifics of the biofuel policies, the definition of the baseline, the time frame for the comparison, types of biofuels included and the models and methods utilized.[1,4,5].

To reduce the potential for ILUC offsetting at least a part of the carbon savings generated by displacing fossil fuels with biofuels, legislation establishing the RFS and the California LCFS require inclusion of the direct- and ILUC-related carbon intensity of a biofuel in determining its total carbon intensity for compliance with these regulations[6,7]. The ILUC-related carbon intensity is biofuel-specific and is referred to as the 'ILUC factor' of that biofuel. The ILUC factor is a measure of the carbon emissions released per unit of biofuel, due to land use change domestically and internationally caused by the biofuel induced change in food/feed crop prices in the US. It is feedstock-specific and higher for feedstocks that require greater diversion of productive cropland from food crop production to biofuel production. The inclusion of the ILUC related carbon intensity of a biofuel in the carbon intensity of a biofuel for compliance with the LCFS is intended to lead to internalization of these indirect effects and create incentives to shift the mix of biofuels towards those with low ILUC effects, thereby increasing the abatement of global carbon emissions. However, this approach and the ILUC factors used for the California LCFS have been controversial and the subject of lawsuits by biofuel producers [8].

There is a large literature assessing the magnitude of the ILUC effect of corn ethanol using global equilibrium models[9]. A few studies have also estimated the ILUC effect of cellulosic biofuels from various feedstocks.[10,11] These studies obtain widely differing estimates ranging from 13-104 g CO_2e Mega-Joule $(MJ)^{-1}$ for corn ethanol and from 5.8-111 g CO_2e MJ^{-1}

for cellulosic biofuels[11] (Supplementary Table 1), depending on choice of model[9,12,13] and underlying assumptions[9,11,12,14]. The first study to quantify the ILUC effect by Searchinger et al.[10] obtained the largest values for the ILUC factor in this range for both corn ethanol and cellulosic ethanol. These large estimates have been shown to result from a number of restrictive assumptions in the modeling analysis including those about the rate of growth of crop productivity, the availability of idle land for conversion to crop production and the ease of conversion of land from one use to another[9,15]. Subsequent estimates obtained using alternative modeling approaches by the USEPA[16] for implementing the RFS and by the California Air Resources Board (CARB)[17] for implementing the LCFS were substantially lower due to differences in the model structure and parametric assumptions [18,19]. Several studies have examined the effect on carbon emissions of various biofuel policies, including the RFS[4,14,20–23], volumetric tax credits[20,21] and a national LCFS[14,24]. Others have examined the land use effect of the RFS[4,14,20] and a national LCFS in the US[24] and internationally[25]. None of these studies examined the economic effects and emissions implications of including an ILUC factor when implementing a LCFS[7,9,12,13,26].

For this study, we used an integrated modeling approach[21] to analyze the economic and carbon emissions effects of supplementing the RFS with a national LCFS and the implications of implementing the LCFS with and without an ILUC factor over the 2007-2027 period. A national LCFS does not currently exist but some states (California and Oregon in the US and British Colombia in Canada) have established LCFS policies. Various states in the Northeast, Mid-Atlantic and Midwestern regions of the US have been investigating the design of an LCFS. A policy similar to the LCFS (the Fuel Quality Directive) has also been implemented in the European Union. It is, therefore, important to analyze about the efficacy of including an ILUC factor in the implementation of a LCFS and inform the design of the LCFS before there is widespread legislation establishing it. This paper provides a general framework to conduct such an analysis that can be implemented at any spatial scale.

We undertook this analysis at the national level by combining the Biofuel and Environmental Policy Analysis Model (BEPAM-F)[14,21,27], with DayCent[28–31]. BEPAM-F is a dynamic, open economy, integrated model of the agricultural, forestry and transportation sectors in the US. DayCent is a globally validated ecosystem model which simulates the direct effects of land use change on soil carbon and nitrogen cycling. Our analysis included the potential to produce biofuels from various feedstocks, including corn and soybeans, sugarcane, crop and forest residues and perennial energy crops like miscanthus, switchgrass and others. We estimated spatially heterogeneous feedstock-specific direct life-cycle carbon emissions intensity of biofuel using parameters from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model for above-ground emissions and DayCent for soil carbon sequestration. We used feedstock-specific ILUC factors from three sources: CARB[32], EPA[33] , and Searchinger[10] . Since all studies did not estimate ILUC factors for all the feedstocks considered here, we imputed values from other studies as shown in Supplementary Table 2. These ILUC factors provided an estimate of the carbon emissions intensity of a unit of biofuel due to land use change both domestically and internationally caused by the change in crop prices and returns to land induced by biofuel production. We included the ILUC factor estimates by Searchinger[10], despite their limitations, in the spectrum of ILUC factors considered to analyze and illustrate the economic and carbon emission consequences of these extremely large ILUC factors in implementing a LCFS.

The baseline scenario (No_LCFS) was defined as one in which only the RFS is implemented over the 2007-2027 period[14] (Supplementary Figure 1). We then supplemented the baseline with two alternative LCFS scenarios, defined as 'with' and 'without' the inclusion of the ILUC factor in the carbon intensity of biofuels. Both LCFS scenarios set the same targets for reducing the average carbon intensity of fuel over the 2017-2027 period. In the 'without' scenario (LCFS_No_ILUC factor), we considered only the direct life cycle carbon intensity of a biofuel (including the carbon intensity due to direct land use change[34]) to determine compliance with the LCFS. In the 'with' scenario (LCFS_With_ILUC factor) the sum of the ILUC factor and the direct life cycle GHG intensity of a biofuel was considered. Three cases of the LCFS_With_ILUC factor scenario were simulated using feedstock-specific ILUC factors from CARB[32], EPA[33] , and Searchinger[10].

The RFS and LCFS policy targets varied over time, thus, the mix and quantities of biofuels and fuels and their economic and carbon emission effects differed over time during the 2007-2027 period. To account for the complete effect of these policies over time, we compared the cumulative 'global' emissions between different scenarios. Cumulative emissions were defined as the sum of the direct emissions from the agricultural, forestry and transportation sectors in the US and the ILUC-related emissions from biofuels over the 2007-2027 period. We used the feedstock-specific ILUC factors for estimating the cumulative ILUC-related emissions in each of the three cases of the LCFS_With_ILUC factor scenario. We estimated the change in cumulative emissions in each of the three cases of the LCFS_With_ILUC factor scenario relative to the LCFS_No_ILUC_factor scenario and relative to the No_LCFS scenario. A comparison of the cumulative emissions in each of the three cases of the LCFS_With_ILUC factor scenario with those under the LCFS_No_ILUC factor scenario provided an assessment of the additional abatement achieved globally due to the inclusion of the ILUC factor in each case.

To estimate the economic effects of this abatement, we measured the change in present value of social welfare, defined by the discounted sum of the changes in consumer, producer and government surplus across the agricultural, forestry and transportation sectors over the 2007-2027 period in each of the three cases of the LCFS_With_ILUC scenario relative to the LCFS_No_ILUC factor scenario. We divided each of these three estimates of the difference in economic surplus between the 'with' and 'without' scenarios by the additional cumulative emissions abated in each case over the 2007-2027 period to obtain a case-specific estimate of the cost of this additional abatement. We compared this cost of abatement to the average social cost of carbon[35] which is a measure of the monetary value of the damages due to carbon emissions to determine if the ILUC factor approach resulted in a positive or negative net societal benefit.

Results

Implicit Taxes and Subsidies Under the LCFS: The RFS and the LCFS policies implicitly tax gasoline and diesel and subsidize biofuels[14,36]. Unlike the RFS, the implicit tax on fossil fuels and implicit subsidy on low carbon biofuels is based on their carbon intensities. These implicit taxes and subsidies are determined by an implicit price per unit of carbon that is the same for all fuels and depends on the stringency of the LCFS target relative to the baseline and by a fuel-specific difference between the fuel's carbon intensity and the target for average fuel carbon intensity set by the LCFS. Fuels with carbon intensity higher than the standard are implicitly taxed (such as fossil fuels) while those with carbon intensity lower than the standard (such as biofuels) are implicitly subsidized. The inclusion of the ILUC factor in the carbon intensity of biofuels increases the difficulty and thus the implicit price of carbon for achieving a given LCFS target by making biofuels more carbon intensive. This increases the implicit tax on fossil fuels and creates greater incentives to reduce their consumption. The inclusion of the ILUC factor also reduces the difference between the carbon intensity of a biofuel and the LCFS target. The impact of this on the implicit subsidy for a biofuel is ambiguous and will differ across biofuels; it will increase the implicit subsidy for biofuels with low ILUC factors and reduce the implicit subsidy (or even implicitly tax) biofuels with high ILUC factors. This will thereby induce a shift from biofuels with relatively high ILUC factors towards biofuels with low ILUC factors.

We found the implicit carbon price under the LCFS_No_ILUC scenario to be \$81 Mg CO_2e^{-1}. The extent to which the inclusion of the ILUC factor increased this implicit carbon price varied across the three cases considered. The CARB, EPA and Searchinger ILUC factors raised the implicit price of carbon by 25%, 30% and 192%, respectively relative to the LCFS_No_ILUC factor scenario (Figure 2). This increased the implicit tax per liter on fossil fuels (gasoline and diesel) and lowered the implicit subsidy on corn ethanol and energy crops for cellulosic biofuels (Figure 1); the high Searchinger ILUC factor for corn ethanol converted the implicit subsidy on corn ethanol under the LCFS_No_ILUC scenario to a tax. All three sets of ILUC factors (particularly the Searchinger factor) increased the implicit subsidy for crop residues due to their negligible ILUC factor (Supplementary Table 1). The Searchinger factors also increased the implicit subsidy for certain energy crops (such as willow, poplar and energy cane that were assumed to have a zero ILUC factor while reducing the implicit subsidy for other energy crops (miscanthus and switchgrass) with very high ILUC factors to zero (Supplementary Table 2).

Effects on Consumption of Alternative Fuels and Land Use: Under the No_LCFS scenario there is 57 billion liters of corn ethanol and 70 billion liters of cellulosic ethanol (of this 47 billion liters are from crop residues and the rest from perennial energy crops) in 2027 (Supplementary Table 3). The implementation of the LCFS_No_ILUC factor increases the implicit subsidies for cellulosic biofuels and increases their volume to 110 billion liters, with most it produced from cellulosic feedstocks, while reducing the amount of corn ethanol to 19 billion liters.

The addition of an ILUC factor in all three cases (CARB, EPA and Searchinger) reduced the demand for fossil fuels and corn ethanol and increased reliance on cellulosic ethanol; however, the composition of feedstocks for the cellulosic biofuels differed across the three cases. Production of corn ethanol decreased by 18-19 billion liters to levels close to zero in all three cases relative to the LCFS_No_ILUC factor scenario (Figure 3). The CARB factors led to an 8- and 11-billion-liter increase in cellulosic ethanol from energy crops and corn stover ethanol consumption respectively. The inclusion of the Searchinger ILUC factors reduced perennial grass ethanol from all sources by 27 billion liters (Supplementary Table 3). It also affected the mix of energy crops used to produce ethanol by switching away from those with high ILUC factors such as miscanthus and switchgrass to other perennials, such as energy cane, willow and poplar (Supplementary Table 2). Production of corn stover ethanol increased by 47-billion liters relative to the LCFS_No_ILUC scenario. Despite the assumed ILUC factor for corn stover being the same in all three cases, the larger consumption of corn stover in the Searchinger case was due to limited cost-effective feedstock alternatives with a low ILUC factor. Consequently, this case resulted in a high carbon price and a larger implicit subsidy for corn stover (Figures 2,3). The additional demand for cellulosic biofuels in all three cases of the LCFS_With_ILUC factor scenario resulted in a higher price of biomass compared to the $79

Mg^{-1} level in the No_LCFS scenario (Figure 2). Biomass price increased by 9%, 13% and 167% under the CARB, EPA and Searchinger cases, respectively.

Under the No_LCFS scenario 13.7 million hectares of land were used in 2027 to produce the corn needed to meet the corn ethanol mandate of 56 billion liters (Supplementary Table 3). This estimate was significantly smaller than the 60 million hectares estimated in Chakravorty et al.[4] because they assumed that the lowest quality cropland (with a yield of 1.7 Mg hectare^{-1}) would be used for producing corn for ethanol. We assumed that average quality land with a yield of 10.3 Mg hectare^{-1} would be used for corn for ethanol production in 2027. EIA estimates for land used to produce 14.2 billion gallons in 2014 indicate a yield of 9.8 Mg hectare^{-1} [37] while USDA estimates of corn yields in 2015 are 10.6 Mg hectare^{-1} [38]. Our findings were similar to those in Hertel et al. [39] who found that 15 million hectares of land would be used for corn for ethanol assuming a 2001 corn yield of 8.5 Mg hectare^{-1}. Our findings were also similar to Chen et al.[14] who found that 11.6 million hectares of land would be used to produce 15 billion gallons of corn ethanol in 2039. We also found that 4.2 million hectares of land would be needed to produce 18.8 billion gallons (70 billion liters) of cellulosic ethanol (from all feedstocks) including crop residues) in the No_LCFS scenario. This was close to the 4.2 million hectares of land needed to produce 16 billion gallons of cellulosic biofuel in 2030 in Hudiburg et al.[21] but much smaller than the 11 million hectares required to produce 21 billion gallons in Chakravorty et al.[4]. This was largely because Chakravorty et al. [4] did not consider the potential to produce biofuels from crop residues which requires no diversion of land.

The implementation of the LCFS ‘with’ and ‘without’ the ILUC factors resulted in a change in land use relative to the No_LCFS scenario (Supplementary Table 1). The LCFS_No_ILUC factor resulted in a reduction in demand for corn ethanol and a shift towards energy crops. Land under corn for ethanol declined to 4.6 million hectares while that under energy crops for cellulosic biofuels increased to 23 million hectares (Supplementary Table 4). The LCFS_With_ILUC factor further exacerbated this shift away from corn ethanol to cellulosic biofuels. Land under energy crops increased to 24 to 30 million hectares under the three cases of the LCFS_With_ILUC factor scenario. Land under crop production for food, feed and fiber was marginally higher in the LCFS_With_ILUC factor scenario in the CARB and EPA cases and marginally lower in the Searchinger case.

Carbon Emissions and Welfare Effects: The estimated US carbon emissions (including those due to ILUC) ranged between 44 and 46.2 B Mg CO_2e in the No_LCFS scenario across the three sets of ILUC factors (Table 1). These declined by 1.9% (=(43.2-44.0)/44)) to 5.1% (=(43.9-46.2)/46.2)) in the LCFS_No_ILUC factor scenario relative to the No_LCFS scenario (percentage estimates are prior to rounding off of carbon emission estimates). The largest decline was observed in the Searchinger case and occurred largely because of the high baseline emissions in this case in the No_LCFS scenario due to the high ILUC factor for corn ethanol. The implementation of the LCFS_With_ILUC factor led to an additional abatement of 1.3% to 2.6% relative to the LCFS_No_ILUC factor scenario. This amounted to 0.6-1.1 B Mg CO_2e across the three cases.

The LCFS_No_ILUC policy increased the economic surplus of food and fuel consumers while adversely affecting fossil fuel producers. There was a small net increase in the discounted value of cumulative economic surplus (2007-2027) by $35 billion relative to the No_LCFS baseline (by 0.13%), assuming a 3% discount rate (Table 1). This was different from the result obtained in Huang et al.[24] which showed a slight decline (0.17%) in social welfare in the LCFS_No_ILUC scenario relative to the No_LCFS scenario. This was due to higher values for the direct carbon intensities of energy crop feedstocks assumed in that study that were based on previous literature. The carbon intensity of energy crops assumed here were based on a calibrated and validated DayCent model and were significantly lower, resulting in lower costs of implementing the LCFS. Chen et al.[14] found that a national LCFS implemented by itself would lead to an increase in US social welfare by $33.4 B over the 2007-2030 period relative to a no-policy scenario.

The additional cost of implementing the LCFS was estimated as the difference in discounted social welfare between the LCFS_No_ILUC and LCFS_With_ILUC scenarios. As compared to the LCFS_No_ILUC scenario, the higher implicit tax on fossil fuels and the lower implicit subsidy on biofuels increased the price of fuel for consumers and lowered the price received by agricultural and fuel producers; the net loss in economic surplus for producers ranged from $20 to $80 billion (Figure 4; Supplementary Table 4). The net reduction in total consumer surplus ranged from $15 to $131 billion. These losses were largest with the Searchinger factors. The overall reduction in social welfare for consumers, producers and government across the sectors considered here ranged between $35 and $211 B. It was highest with the Searchinger factors and lowest with the CARB factors. Over half of this loss in economic surplus was borne by the fuel consumers (Figure 4, Supplementary Table 4).

We divided the additional cost by the additional abatement achieved with the inclusion of the ILUC factor (0.6-1.1 B Mg CO_2e) to obtain the per metric ton cost of abatement. We found this ranged from $61 Mg CO_2e^{-1} (=$35B/0.6 B Mg CO_2e) to $187 Mg CO_2e^{-1} (=$211B/1.1 B Mg CO_2e). These costs were substantially higher (20%-270%) than the average social cost of carbon of $50 Mg CO_2e^{-1} with the same 3% discount rate assumed here[35] (Table 1).

There is wide disparity in the range of estimates of the social cost of carbon [40] but considerable consensus that \$50 Mg CO_2e^{-1} is a reasonable estimate. Following an extensive review of the estimates of the social cost of carbon in the literature, Tol (2005)[41] concluded that the social cost of carbon in 2030 was unlikely to exceed \$50 Mg CO_2e^{-1}, under standard assumptions about discounting and aggregation. Based on a similar review, Watkiss and Downing (2008)[42] found that \$50 Mg CO_2e^{-1} provided a reasonable benchmark for global decision making seeking to reduce the threat of dangerous climate change and including a modest level of aversion to extreme risks, relatively low discount rates and equity weighting. Most recently Havranek et al. (2015) [43] conducted a meta-analysis of estimates of the social cost of carbon in the literature and found that the upper boundary for mean estimates of the social cost of carbon reported by studies after controlling for various factors (including publication bias) was \$39 Mg CO_2e^{-1}. Estimates of the social cost of carbon have a skewed, right-tailed distribution[35]. This implies a relatively smaller likelihood of their exceeding the cost of abatement estimated here than of being lower than it. Cost of abatement with the Searchinger factors (\$187 Mg CO_2e^{-1}) was higher than even the 95^{th} percentile of the social cost of carbon of \$152Mg CO_2e^{-1} with the same 3% discount rate assumed here.

We examined the sensitivity of our findings to several key parameters assumed here by considering alternative values for: the elasticity of supply of gasoline from the rest of the world, feedstock yields, cost of conversion to ethanol and carbon emissions due to conversion of marginal land to cropland (Supplementary Figure 2). We found that these costs of abatement could increase significantly under more conservative assumptions about the yields and availability of marginal land for perennial grasses and the costs of producing cellulosic biofuels. Cost of abatement ranged between \$54-\$94 Mg CO_2e^{-1} with the CARB factors; corresponding ranges were \$63-\$107 with the EPA factors and \$162-\$199 with the Searchinger factors. Lastly, we investigated the sensitivity to the discount rate by increasing it from 3% to 5%. Cost of abatement with a 5% discount rate was \$45-\$122 Mg CO_2e^{-1}. These costs were 181% to 662% higher than the correspondingly lower average social cost of carbon of \$16 Mg CO_2e^{-1} in 2030[35].

Discussion

Our analysis examined the efficacy of an ILUC factor approach while implementing a national LCFS. We estimated the additional cumulative carbon abatement that would be achieved by including the ILUC factor as a part of the carbon intensity of biofuels when evaluating their potential for compliance with a LCFS relative to the cumulative emissions with an LCFS without including an ILUC factor over the 2007-2027 period. We also estimated the change in discounted value of social welfare cumulated over the 2007-2027 period due to the inclusion of the ILUC factor in implementing the LCFS. We compared the welfare cost of abatement per unit of carbon emissions to the monetary value of the benefits of the additional abatement as estimated by the social cost of carbon.

We found that the inclusion of the ILUC factor in implementing the LCFS imposed additional costs on fuel consumers and fuel producers because it lowered the implicit subsidy on several types of biofuels while raising the implicit tax on fossil fuels. It led to additional abatement of cumulative emissions over 2007-2027 by 0.6-1.1 B Mg CO_2e compared to those without an ILUC factor, depending on the ILUC factors utilized. The cost of this additional abatement to the US ranged from \$61 to \$187 Mg CO_2e^{-1} and was substantially greater than the social cost of carbon of \$50 Mg CO_2e^{-1} in 2030, assuming a 3% discount rate. A higher discount rate of 5%, lowered the cost of abatement to \$45-\$122 Mg CO_2e^{-1}. These costs were 181% to

662% higher than the correspondingly lower average social cost of carbon of \$16 Mg CO_2e^{-1} in 2030. Our analysis, therefore, showed that the ILUC factor approach to reducing ILUC-related carbon emissions with a LCFS did not result in positive net social benefits.

Studies have suggested other approaches for regulating ILUC emissions, including explicit incentives for high yielding feedstocks that can be grown with minimal diversion of land from food production, certification of low indirect impact biofuels and direct regulations to restrict conversion of non-cropland and forestland to crop production[1,4,7]. We leave it to future research to examine the cost-effectiveness of such approaches compared to that of an ILUC factor approach.

Methods: BEPAM-F (Biofuel and Environmental Policy Analysis Model with Forestry), is a spatially explicit multi-market dynamic open economy model that determines the market equilibrium by maximizing the sum of consumers' and producers' surpluses in the agricultural, forestry, and transportation fuel sectors in the US subject to various material balance, technological, land availability, and policy constraints over the 2007-2027 period. The model includes crop, forest and pastureland in the US with the potential for conversion of land from one use to another based on the net returns to land under various uses subject to some constraints. Model structure, parameterization and validation were explained in previous studies[14,21,24].

The transportation sector incorporates demand for Vehicle Kilometers Travelled with various types of vehicles that generate a derived demand for liquid fossil fuels and biofuels that include first- and second- generation biofuels. Gasoline is produced domestically and imported. The agricultural and forestry sectors produce a broad range of crop, livestock, bioenergy and forest products that compete for land. The prior application of BEPAM-F[21] focused on analyzing the feedstock mix, land use and GHG implications of a cellulosic biofuel mandate over the 2007-2022 period.

A key extension of BEPAM-F here is the imposition of a LCFS constraint that restricts the ratio of the sum of the GHG emissions with each type of fossil fuel and biofuel consumed (defined as the sum of the product of the GHG intensity of each fuel and the quantities of those fuels consumed) to the sum of the energy from these fuels to be less than the targeted standard. The GHG intensity of each type of biofuel feedstock included below-ground changes in soil carbon and above-ground emissions. We simulated the soil organic carbon changes and associated direct N_2O, CH_4, NO_3 leaching for each modeled crop using DayCent[21,29,31]. DayCent calculates plant growth as a function of water, light, and soil temperature, and limits actual growth based on soil nutrient availability. In addition to soil carbon uptake and loss, the DayCent model was also used to simulate harvested yields, direct N_2O emissions (indirect calculated using IPCC Tier 1 factors), nitrate leaching, and methane flux. Model parameterization, calibration, and validation were completed in prior studies[21,29] . The direct above-ground lifecycle GHG intensity of each of the biofuel pathways was estimated by adapting the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model as in Dwivedi et al (2015)[34]. Both the below-ground and above-ground emissions vary spatially. As a result, the GHG intensity of the overall transportation fuel depended on the mix of feedstocks and the spatial location where they were produced.

The model endogenously determined domestic land use change, production levels and market prices of food crops, fossil fuels, biomass and land, and the corresponding GHG emissions from the three sectors. With the LCFS constraint, the model endogenously determined the mix of feedstock, the locations to grow them in taking into account the spatially varying direct GHG intensity of biofuels, the implicit price of carbon, the fuel-specific implicit taxes/subsidies. In each of the scenarios, we examined the cumulative change (summed over 2007-2027) in global GHG emissions which was the sum of the emissions from the US transportation, agricultural and forestry sectors (including the direct emissions from biofuel production and soil carbon sequestration) and the emissions due to the scenario-specific ILUC effect in the rest of the world due to biofuels. The three policy scenarios simulated here are:

1. No LCFS Baseline: A mandated level of biofuel production based on the RFS established by EISA, 2007 was imposed as a blend mandate as in[14] (Supplementary Figure 1). Unlike the RFS which mandated blending of 36 billion gallon (136.3 billion liters) of ethanol with gasoline by 2022 (considered earlier in[29]) with an implicit upper limit of 15 billion gallons on

corn ethanol, we imposed a lower mandate of 35 billion gallons (131.5 billion liters) by 2027 with a maximum of 15 billion gallons of corn ethanol, assuming the remaining volumes could be met by sources not included in the model such as municipal solid waste, animal fats and waste oil. Sugarcane ethanol imports from Brazil were allowed with the level determined endogenously based on competitiveness with corn ethanol and cellulosic ethanol, up to a maximum of 4 billion gallons.

2. LCFS_No_ILUC factor: The RFS in Scenario 1 was supplemented by a LCFS imposed in 2017 to achieve a targeted reduction in average fuel carbon intensity of 15% by 2027 relative to the level in 2007. The GHG intensity of biofuels here included only the direct life-cycle emissions.

3. LCFS_With_ILUC factor: This scenario is the same as Scenario 2, except that the GHG intensity of biofuels included both the direct life-cycle emissions and ILUC related emissions intensity obtained from three existing studies, CARB[20], EPA[21], and Searchinger[22].

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Supplementary Information is available.

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Author Contributions

M.K. and W.W. designed and implemented the study with help from T.H. and E.D. M.K., W.W., E.D., and T.H. co-wrote the paper.

Author Information

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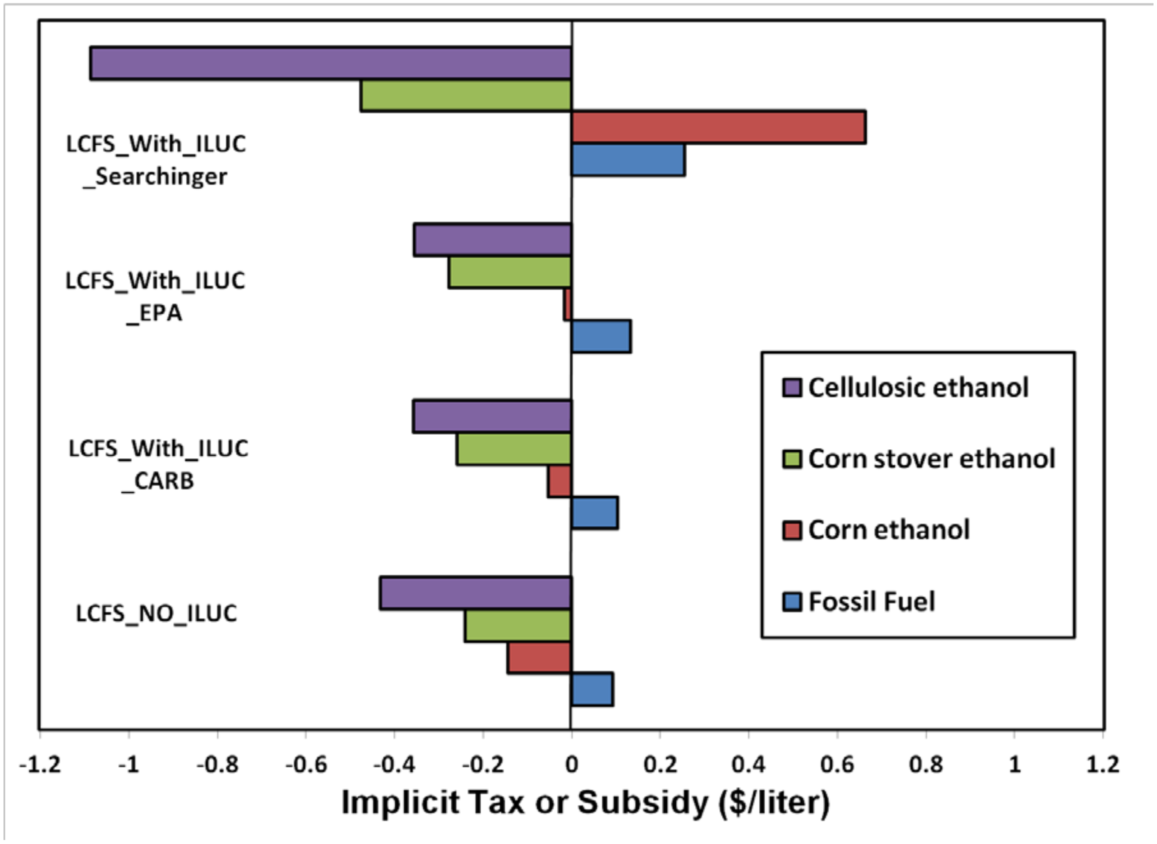
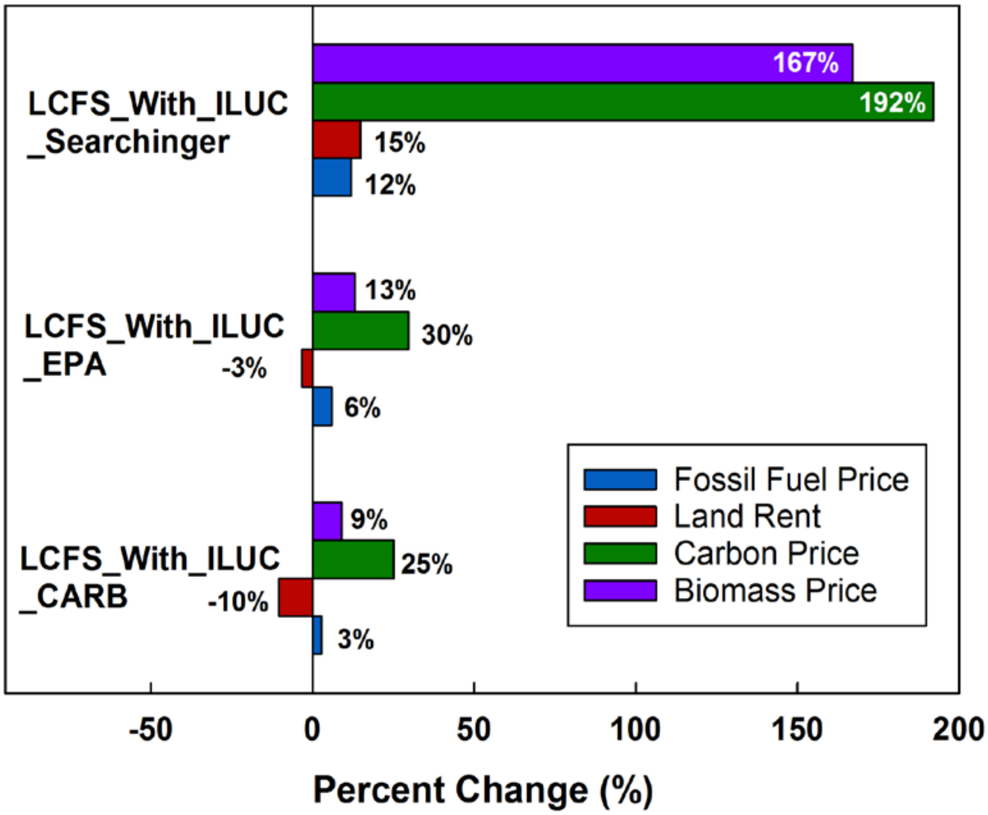
Figure 1. The implicit fuel taxes or subsidies in US dollars per liter without ILUC (LCFC_No_ILUC) and with ILUC (LCFS_With_ILUC) factor from Searchinger[22], the US EPA[21], and the California Air Resources Board (CARB)[20].



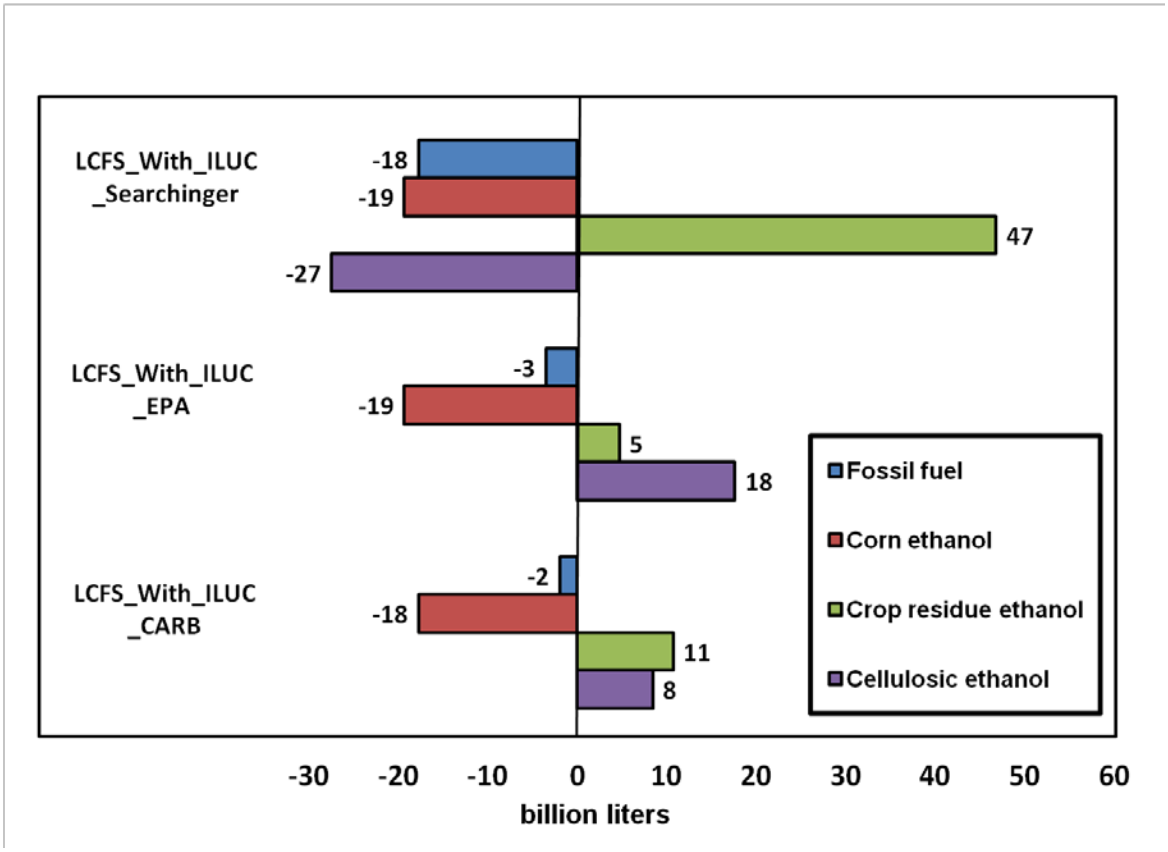
The positive values represent a tax while negative values represent a subsidy on the fuel. Cellulosic ethanol (purple) includes ethanol produced from cellulosic biomass from miscanthus, switchgrass and other perennial energy crop feedstocks shown in Supplementary Table 2, corn stover ethanol (green) is produced from cellulosic biomass in corn residues, corn ethanol (red) is from corn grain, and fossil fuels (blue) include gasoline and diesel.

Figure 2. Percentage change in various prices in the LCFS_With_ILUC factor (Searchinger, EPA, and CARB) relative to the LCFS_No_ILUC factor scenario.



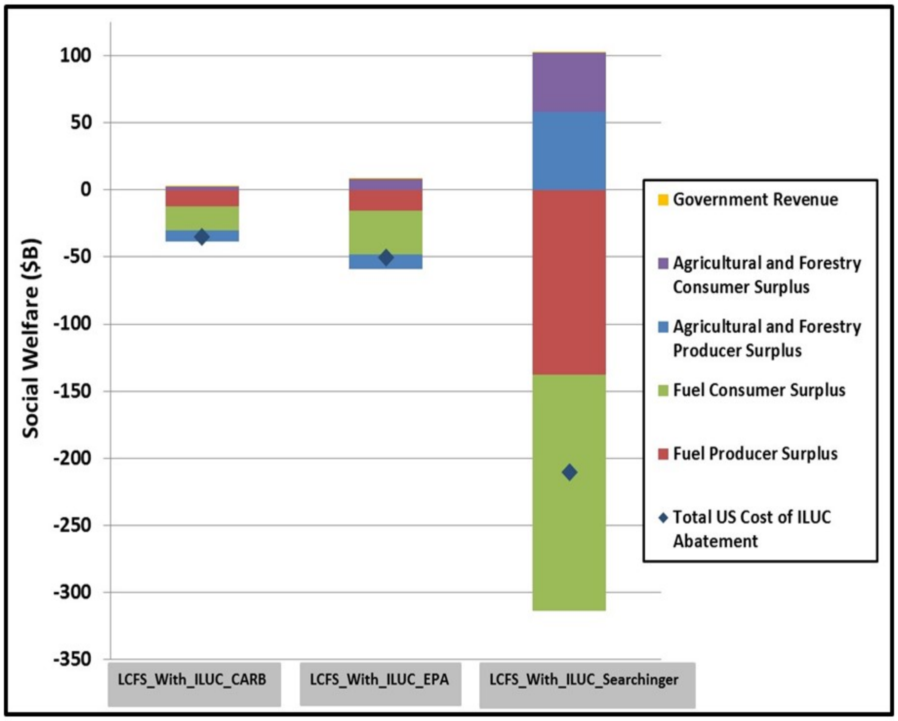
Fossil fuel price (blue) is the weighted average price of gasoline and diesel fuel price.

Figure 3. Change in fuel consumption in the LCFS_With_ILUC factor (Searchinger, EPA, and CARB) relative to the LCFS_No_ILUC factor scenario is in billions of liters.



Fossil fuel (blue) includes gasoline and diesel; crop residue ethanol (green) includes corn stover and wheat straw ethanol; Cellulosic ethanol (purple) includes ethanol from perennial energy crops, miscanthus, switchgrass, energy cane, poplar and willow.

Figure 4. Effects of each ILUC factor (Searchinger, EPA, and CARB) on the discounted value of economic surplus (Social Welfare) in billions of dollars relative to an LCFS_No_ILUC factor scenario.



Surpluses are divided into five categories: government revenue (orange), agricultural and forestry consumer (purple), agricultural and forest producer (blue), fuel consumer (green), and fuel producer (red). The total US cost of abatement by including the ILUC factor is represented by the dark blue diamond; this net cost is the sum of the change in discounted value of the economic surplus of consumers and producers in the agricultural, forestry and transportation sectors and the government surplus over the 2007-2027 period between the LCFS_With_ILUC and LCFS_No_ILUC factor cases as shown in Table 1. These net costs are $35.1 billion with CARB factors, $50 billion with EPA factors and $210.5 billion with Searchinger factors. The disaggregation of these costs is shown in Supplementary Table 4.

Table 1: Cumulative Carbon Emissions and Social Welfare Under Alternative Scenarios (2007-2027)

Scenario	No_LCFS Baseline			LCFS_No_ILUC Factor			LCFS_With_ILUC Factor		
	CARB	EPA	Search-inger	CARB	EPA	Search-inger	CARB	EPA	Search-inger
1. US Direct GHG Emissions (B Mg CO_2e)	43.5			42.7			42.2	42.1	41.8
2. US GHG Emissions (incl. ILUC) (B Mg CO_2e)	44.0	44.2	46.2	43.2	43.5	43.9	42.6	42.8	42.7
3. Percentage Change in Emissions Relative to No_LCFS Scenario[a]				-1.9%	-1.7%	-5.1%	-3.2%	-3.3%	-7.6%
4. Change in Emissions with ILUC Relative to No_ILUC Scenario[b] (B Mg CO_2e)							0.6	0.7	1.1
5.Percentage Change in Emissions Relative to No_ILUC Scenario[c]							-1.3%	-1.6%	-2.6%
6.US Social Welfare ($B)	27514			27549			27513	27498	27338
7.Social Welfare Cost of LCFS ($ B)				-35 [d]			0.2[e]	15 [e]	176 [e]
8.Additional US Abatement Cost Due to ILUC ($ B)[f]							35	50	211
9.Additional US Cost of Global Abatement Due to ILUC ($/Mg CO_2e)[g]							60.7	73.7	186.6

[a.] (Emissions with LCFS- Emissions with No_LCFS)/Emissions with No_LCFS
[b.] Emissions with LCFS_No_ILUC minus Emissions with LCFS_With_ILUC
[c.] (Emissions with LCFS_With_ILUC minus Emissions with LCFS_No_ILUC)/ Emissions with LCFS_NO_ILUC
[d.] Social Welfare with No_LCFS minus Social Welfare with LCFS_No_ILUC; negative value indicates a welfare gain with LCFS relative to No LCFS.
[e] Social Welfare with No_LCFS minus Social Welfare with LCFS_With_ILUC; positive value indicates a loss in welfare due to the addition of the ILUC factor relative to the LCFS_No_ILUC scenario.
[f.] Social Welfare with LCFS_No_ILUC factor minus Social Welfare in LCFS_With_ILUC factor; positive value indicates a loss in social welfare due to the addition of the ILUC factor relative to the LCFS_No_ILUC factor.
[g.] 'Additional US Abatement Cost Due to ILUC' divided by 'Change in Emissions with ILUC Relative to No_ILUC Scenario' (Row9=Row 8/Row 4)