The Economic Cost of Including the Indirect Land Use Factor in Low Carbon Fuel Policy: Efficiency and Distributional Implications

Madhu Khanna
Department of Agricultural and Consumer Economics
University of Illinois at Urbana Champaign
1301 Gregory Dr, Urbana, IL 61801
Email: khanna1@illinois.edu

Weiwei Wang
Department of Agricultural and Consumer Economics
University of Illinois at Urbana Champaign
1301 Gregory Dr, Urbana, IL 61801
Email: wwwang@illinois.edu

Tara W. Hudiburg
Department of Forest, Rangeland and Fire Sciences
University of Idaho
875 Perimeter Drive, Moscow, ID 83863
Email: thudiburg@uidaho.edu

Evan H. DeLucia
Department of Plant Biology
University of Illinois at Urbana Champaign
1206 W. Gregory Drive, Urbana, IL 61801
Email: delucia@life.illinois.edu

Selected Paper prepared for presentation at the 2016 Agricultural & Applied Economics Association Annual Meeting, Boston, Massachusetts, July 31-August 2

The Economic Cost of Including the Indirect Land Use Factor in Low Carbon Fuel Policy: Efficiency and Distributional Implications

Abstract

Concerns about the indirect land use change (ILUC) caused by biofuels has led to the inclusion of an ILUC factor as a part of the greenhouse gas (GHG) intensity of biofuels in low carbon fuel policies. Here, we develop an integrated modeling framework to simulate the effects of including an ILUC factor in a national Low Carbon Fuel Standard (LCFS) and to assess the variability of these effects depending on the ILUC factor used. We found that additional GHG abatement achieved over the 2017-2027 period ranged from 0.6 to 1.2% while the additional economic costs to the US ranged from \$35 to \$211 billion depending on the biofuel-specific ILUC factors utilized; more than half of these costs were borne by domestic fuel consumers. The implied per metric ton cost of the additional abatement ranged from \$64 to \$197 and was substantially larger than the \$50 per metric ton social cost of carbon estimated by the US government.

Introduction

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 by inducing a switch towards biofuels. While the RFS sets a quantity mandate for different types of biofuels that differ in their GHG intensity relative to gasoline, an LCFS sets a target for reducing the average fuel carbon intensity (AFCI) of transportation fuel below the baseline year level and provides blenders the flexibility to select the quantities of different types of biofuels based on their costs and GHG intensity relative to the standard. The production of biofuels has raised concerns about their competition for land with food crops resulting in higher global food crop prices that can lead to indirect land use change (ILUC) by creating incentives for the conversion of non-cropland to crop production globally. This ILUC effect has the potential to release carbon stored in soils and vegetation(Anderson-Teixeira et al. 2012) and offset at least a part of the savings generated by displacing fossil fuels with biofuels. This has led to legislation establishing the RFS and the California LCFS to require inclusion of the ILUC-related GHG intensity (referred to as the 'ILUC factor') in determining its compliance with these regulations (Rajagopal 2014).

Several studies have estimated the ILUC effect of biofuels using global equilibrium models, obtaining widely differing estimates ranging from 13-104 g CO_2/MJ for corn ethanol and from 5.8-111 g CO_2/MJ for cellulosic biofuels (Taheripour and Tyner 2013) (Table 1), depending on the choice of model (Khanna and Crago 2012; Plevin et al. 2010; Zilberman, Hochman and Rajagopal 2011) and underlying assumptions (Khanna and Crago 2012; Plevin et al. 2010; Taheripour and Tyner 2013; Chen et al. 2014). Several studies have examined the GHG savings that could be realized by various biofuel policies, including the RFS (Chen et al. 2014; Chen, Huang and Khanna 2012; Hudiburg et al. 2016; Bento, Klotz and Landry 2012; Beach and McCarl 2010), volumetric tax credits (Chen et al. 2012; Hudiburg et al. 2016) and a national LCFS(Chen et al. 2014; Huang et al. 2013). None of these studies, however, examined the economic costs and GHG implications of including an ILUC factor as a part of the GHG intensity of a biofuel when implementing a policy such as an LCFS.

For this study, we used an integrated modeling approach (Hudiburg et al. 2016) to analyze the GHG savings and the economic costs 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. We combined the Biofuel and Environmental Policy Analysis Model (BEPAM), a dynamic, open economy, integrated model of the agricultural, forestry and transportation sectors for the US with the globally validated ecosystem model, DayCent (Parton et al. 1998; Hudiburg et al. 2015; Campbell et al. 2014; Del Grosso et al. 2005) which simulates the direct effects of land use change on soil carbon and nitrogen cycling. which simulates the direct effects of land use change on soil carbon and nitrogen cycling. Our analysis considered biofuels from various feedstocks, including corn, several types of energy crops, and crop residues such as corn stover. We simulated the effects of supplementing the RFS with two LCFS scenarios, defined as ‘with’ and ‘without’ the inclusion of the ILUC factor in GHG intensity of biofuels on the economic costs of GHG abatement (Figure 1). In both LCFS scenarios, the same targets for reducing the AFCI of fuel over the 2017-2027 period relative to the baseline in 2007 are assumed; in the ‘without’ scenario (LCFS_No_ILUC factor), only the direct life cycle GHG intensity of a biofuel, including that due to direct land use change (Dwivedi et al. 2015), is used to determine compliance with the LCFS, while in the ‘with’ scenario (LCFS_With_ILUC factor) the sum of its ILUC related GHG intensity (ILUC factor) and the direct life cycle GHG intensity is included. We considered three alternative estimates of the ILUC factors for each biofuel based on the following sources, CARB(California Air Resources Board 2014), EPA(Environmental Protection Agency 2010) , and Searchinger(Searchinger et al. 2008) (Table 2). Results were compared to a baseline scenario (No_LCFS) in which only the RFS is implemented (volumetric targets for biofuels are converted to a mandated blend rate; Figure 1). We measure economic costs by the change in present value of social welfare, defined by the discounted sum of the changes in consumer, producer and government surplus across the modeled sectors over the 2007-2027 period, in each of the two LCFS scenarios relative to the baseline scenario. Our benchmark analysis assumes a discount rate of 3%.

Methods

BEPAM-F (Biofuel and Environmental Policy Analysis Model with Forestry), is a spatially explicit multi-market dynamic model that determines the market equilibrium by maximizing the sum of consumers' and producers' surpluses in the agricultural, forestry, and transportation fuel sectors subject to various material balance, technological, land availability, and policy constraints over the 2007-2027 period (Hudiburg et al. 2016). The model considers 295 CRDs in 41 US states as spatial decision units and incorporates the heterogeneity in crop and livestock production across these CRDs, where crop yields, costs of production, and resource endowments are specified differently for each CRD and each crop. It incorporates international trade with the rest of the world, in the form of exports of agricultural commodities and imports of gasoline and sugarcane ethanol. The model endogenously determines the domestic land use change, production levels and market prices of food crops, fuels and land, the domestic and global gasoline market displacement effects of biofuels and the corresponding GHG emissions from the three sectors.

The transportation sector incorporates demand for Vehicle Kilometers Travelled with four types of vehicles, including conventional gasoline, flex fuel, gasoline-hybrid, and diesel vehicles that generate a derived demand for gasoline, diesel and biofuels that include first- and second- generation biofuels. Supply curves for domestic gasoline and diesel as well as for gasoline supply and demand in rest of world (ROW) are included to determine the amount of gasoline imports and the price of gasoline and diesel. First generation biofuels include domestically produced corn ethanol and imported sugarcane ethanol, soybean biodiesel, DDGS-derived corn oil, and waste grease. Second-generation biofuels include cellulosic ethanol and biomass-to-liquid diesel that can be blended with gasoline and diesel, respectively. We determined the domestic and international price of gasoline endogenously by the domestic demand for gasoline derived from the downward sloping demands for VMT and the demand for gasoline in the rest of the world and the upward sloping domestic and the rest of the world supply of gasoline. The policy induced increased production of biofuels reduces the domestic demand for gasoline and the US demand for imports from the rest of the world. We incorporated the feedback effect of the biofuel driven reduction in the world and domestic price of gasoline on fuel consumption in the US and the rest of the world and its implications for the GHG savings with biofuels (Chen et al., 2014). We quantified the major factors influencing the above- and belowground GHG balance due to bioenergy crop production and the effects on GHG emissions in each policy scenario, including both domestic and global indirect land-use change and gasoline market rebound effects due to the changes in food and fuel prices induced by biofuel production.

The agricultural sector in the BEPAM-F includes fifteen conventional crops, eight livestock products, various processed commodities, and co-products from the production of corn ethanol and soy diesel. It incorporates a range of feedstocks for second generation biofuels, including energy crops (miscanthus, switchgrass, energy cane, willow and poplar) and crop residues from corn and wheat. The model considers five types of land, namely regular cropland, cropland pasture, CRP land, permanent pasture land, and forestland pasture. Cropland pasture can be converted to row crop or energy crop production if the net returns from land use change are positive while other types of land are assumed to be unchanged over the model horizon. Changes in the mix of crops grown were determined using the methods described in Chen and Önal (2012). Assumptions about the productivity of cropland pasture, the costs of converting it to conventional crops or energy crops, and restrictions on land conversion for energy crop production in a CRD were similar to Hudiburg et al. (2016).

The structure of the forestry sector in BEPAM-F was similar to that in Forest and Agricultural Sector Optimization Model (FASOM) and included 11 forest marketing regions. Forestland was characterized by two types of trees (softwoods and hardwoods) and distinguished by various site productivity classes that determined yield per unit land. Land conversion from one use to another within the sector and across sectors was constrained by pre-defined suitability classes that determined which acres could be converted to forest, crop or pasture.

We used the ecosystem modeled GHG balance (CO_2, N_2O, CH_4) for each crop combined with life cycle emissions to calculate the net GHG emissions for the modeled scenarios. We simulated the associated direct N_2O, CH_4, NO_3 leaching, and soil organic carbon changes for each crop using DayCent (Hudiburg et al. 2016; Hudiburg et al. 2015; Del Grosso et al. 2005). 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 (Hudiburg et al. 2016; Hudiburg et al. 2015). The direct above-ground GHG intensity of each of the biofuel pathways was estimated by conducting spatially explicit life-cycle GHG accounting by adapting the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model as in Dwivedi et al. (2015).

Under each of the two LCFS 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), the emissions due to the ILUC effect domestically and in the rest of the world due to biofuels and the indirect emissions due to a change in gasoline consumption in the rest of the world due to biofuel induced market feedbacks. A description of the three policy scenarios simulated here is as follows:

1. No LCFS Baseline: A mandated level of biofuel production based on the RFS established by EISA, 2007 was imposed. Unlike the RFS which mandated blending of 36 billion gallon (136.3 billion liters) of ethanol with gasoline by 2022 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 the AFCI of 15% by 2027 relative to the level in 2007. The GHG intensity of biofuels included only the direct life-cycle emissions in this scenario.
3. LCFS_With_ILUC factor: This scenario is the same as Scenario 2, except that the GHG intensity of biofuels include both the direct life-cycle emissions and ILUC related emissions intensity obtained from three existing studies, CARB (California Air Resources Board 2014), EPA(Environmental Protection Agency 2010), and Searchinger (Searchinger et al. 2008).

Results

Effects of Alternative Policy Scenarios on Fuel Consumption and Prices

In agreement with previous studies (Chen et al. 2014; Holland et al. 2015), the RFS and the LCFS policies implicitly tax gasoline and diesel and subsidize biofuels. Unlike the RFS, an LCFS imposes an implicit price on carbon that is levied on a fuel based on the difference between its GHG intensity and the AFCI. Fuels with a GHG intensity higher (lower) than the AFCI are implicitly taxed (subsidized) with the magnitude of these taxes (subsidies) being proportional to the difference between a fuel's GHG intensity and the AFCI. Inclusion of the ILUC factor increases the implicit carbon price by increasing the difficulty of achieving the targeted AFCI. However, by raising the GHG intensity of a biofuel it lowers the difference between its GHG intensity and the AFCI. The inclusion of the ILUC factor increased the implicit tax per liter on fossil fuels (gasoline and diesel) and lowered the implicit subsidy on corn ethanol (Figure 2). The Searchinger ILUC factor for corn ethanol converted the implicit subsidy on corn ethanol under the LCFS_No_ILUC factor scenario to a tax. All three sets of ILUC factors increased the implicit subsidy for crop residues due to their relatively low or negligible ILUC factor (Table 1).

We found that inclusion of the CARB and Searchinger ILUC factors raised the implicit price of carbon by 25% and 192%, respectively (Figure 3). This resulted in a corresponding increase in the price of fossil fuels by 3% to 12% leading to a reduction in fossil fuel consumption by 2 to 18 billion liters (0.3-3%) relative to the LCFS_No_ILUC factor scenario (Figure 4). All three sets of ILUC factors reduced the demand for corn ethanol and increased reliance on corn stover ethanol but the effect on perennial grass ethanol was mixed. Inclusion of the CARB factors led to a 7 and 11 billion liter increase in perennial grass and corn stover ethanol consumption, respectively. Corresponding values under the Searchinger factors were a

24 billion liter reduction in ethanol from perennial grasses and a 47 billion liter increase in ethanol from corn stover relative to the LCFS_No_ILUC scenario.

GHG Emissions and Economic Surplus Effects of Alternative Scenarios

Low carbon fuel policies have the potential to affect emissions in the agricultural and transportation sectors beyond the US by leading to changes in global land use and fuel consumption by affecting global food and fuel prices (Hudiburg et al. 2016). We estimated the change in the cumulative 'global' GHG emissions (US and rest of the world) over 2007-2027 period in the LCFS_No_ILUC scenario to be a 1% to 2.6% reduction relative to the US emissions in the No_LCFS baseline scenario (Table 3). The addition of the ILUC factor to the LCFS implementation, increased abatement in these global emissions to 1.6% to 3.8% relative to No_LCFS.

As compared to the No_LCFS case, we found that implementation of the LCFS_No_ILUC factor increased the volume of biofuels blended and shifted the mix towards lower carbon energy crop biofuels. Relative to the No_LCFS scenario, there was an increase in economic surplus for fuel consumers and agricultural consumers and a reduction in the surplus for agricultural producers under the LCFS_No_ILUC scenario with a net increase in social welfare of $35 billion (Table 4).

The addition of the ILUC factors to the LCFS reduced the economic surplus of agricultural and fuel producers with the sum ranging from $21 billion to $80 billion (Figure 5). The addition of the ILUC factors also reduced fuel consumer surplus but led to a relatively small increase in agricultural consumer surplus, leading to a net reduction in total consumer surplus of $15-$131 billion, depending on the ILUC factor. The loss to both consumers and producers was largest with the Searchinger factors with the exception of the effect on agricultural producers. Agricultural producer surplus increased with the Searchinger factors due to the increase in land rents caused by large increase in demand for corn stover which was the only low ILUC factor biofuel pathway in the Searchinger case. Overall, there was a decline in the social welfare in the agricultural, forestry and transportation sectors by $35 to $211 billion in the LCFS_With_ILUC factor scenario compared to the LCFS_No_ILUC factor case. The least negative impact was with the CARB ILUC factors and the largest negative impact was with the Searchinger factors; over half of this loss in economic surplus would be borne by the fuel consumers in the US (Figure 5). The implied average US cost of the additional GHG abatement achieved by including the ILUC factor in the LCFS policy ranged from $64 to $197 per metric ton of abatement. These costs were substantially higher (27%-293%) than the estimated social cost of carbon of $50 per metric ton of CO_2 in 2030 with the same 3% discount rate as assumed here (United States Government 2013) (Table 3).

Sensitivity Analysis

We examined the uncertainty in 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, GHG emissions due to conversion of marginal land to cropland and limits to conversion of land to energy crop production (Figure 6). We found that the per unit cost of abatement ranged between $60-$96 per metric ton of CO_2 with the CARB factors; corresponding ranges were $68-$110 with the US EPA factors and $163-$205 with the Searchinger factors. Lastly, we investigated the sensitivity of our results to the assumed discount rate by estimating the effect of increasing it from 3% to 5%. We found that this lowered the per ton cost of abatement to \$45-\$125 per metric ton of CO_2. However these costs were still significantly higher than the correspondingly lower social cost of carbon of \$16 per ton in 2030 (United States Government 2013).

Conclusions

The inclusion of the ILUC factor in GHG intensity of biofuels to determine compliance with the LCFS increased GHG savings achieved by 0.6-1.1 million metric tons (0.6%-1.2%) relative to a policy without the ILUC factor; the additional savings with the inclusion of the Searchinger factor were almost twice as high as with the CARB factor. However, the use of the Searchinger ILUC factors imposed an economic cost of \$211 billion on the US which was four to six times higher than the welfare cost by imposing the CARB and EPA ILUC factors respectively; these costs were borne by the fuel consumers and producers and were only partially offset by gains to agricultural consumers and producers. The net per ton costs of GHG abatement were \$64, \$77 and \$197 under the CARB, EPA, and Searchinger factors respectively and significantly higher than the estimated social damages due to climate change represented by the social cost of carbon of \$50 per metric ton for 2030 with a 5% discount rate. These results suggest the need for finding other approaches for regulating ILUC emissions that could be more cost-effective than including an ILUC factor in the GHG intensity of a biofuel.

References

Anderson-Teixeira, K.J., P.K. Snyder, T.E. Twine, S.V. Cuadra, M.H. Costa, and E.H. DeLucia. 2012. "Climate-regulation Services of Natural and Agricultural Ecoregions of The Americas." *Nature Climate Change* 2(3):177–181.

Beach, R.H., and B.A. McCarl. 2010. "Agricultural and Forestry Impacts of the Energy Independence and Security Act: FASOM Results and Model Description."

Bento, A.M., R. Klotz, and J.R. Landry. 2012. "Are There Carbon Savings from US Biofuel Policies? The Critical Importance of Accounting for Leakage in Land and Fuel Markets." *The Energy Journal* 36(3):1–89.

California Air Resources Board. 2014. Proposed re-adoption of the low carbon fuel standard. Staff report: initial statement of reasons for proposed rulemaking. Industrial Strategies Division, California Environmental Protection Agency. Available at: http://www.arb.ca.gov/regact/2015/lcfs2015/lcfs15isor.pdf.

Campbell, E.E., J.M.F. Johnson, V.L. Jin, R.M. Lehman, S.L. Osborne, G.E. Varvel, and K. Paustian. 2014. "Assessing the Soil Carbon, Biomass Production, and Nitrous Oxide Emission Impact of Corn Stover Management for Bioenergy Feedstock Production Using DAYCENT." *BioEnergy Research* 7(2):491–502.

Chen, X., H. Huang, and M. Khanna. 2012. "Land-Use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy." *Climate Change Economics* 03(03):1250013.

Chen, X. and H. Önal. 2012. "Modeling Agricultural Supply Response Using Mathematical Programming and Crop Mixes." *American Journal of Agricultural Economics* **94**, 674-686

Chen, X., H. Huang, M. Khanna, and H. Önal. 2014. "Alternative Transportation Fuel Standards: Welfare Effects and Climate Benefits." *Journal of Environmental Economics and Management* 67(3):241–257.

Del Grosso, S., A. Mosier, W. Parton, and D. Ojima. 2005. "DAYCENT Model Analysis of Past and Contemporary Soil NO and Net Greenhouse Gas Flux for Major Crops in the USA." *Soil and Tillage Research* 83(1):9–24.

Dwivedi, P., W. Wang, T. Hudiburg, D. Jaiswal, W. Parton, S. Long, E. DeLucia, and M. Khanna. 2015. "Cost of Abating Greenhouse Gas Emissions with Cellulosic Ethanol." *Environmental Science & Technology* 49(4):2512–2522.

Environmental Protection Agency. 2010. Renewable fuel standard program (RFS2) regulatory impact analysis. Ann Arbor, MI: Assessment and Standards Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available at: https://www.epa.gov/sites/production/files/2015-08/documents/420r10006.pdf.

Holland, S.P., J.E. Hughes, C.R. Knittel, and N.C. Parker. 2015. "Unintended Consequences of Carbon Policies: Transportation Fuels, Land-use, Emissions, and Innovation." *The Energy Journal* 36(3).

Huang, H., M. Khanna, H. Önal, and X. Chen. 2013. "Stacking Low Carbon Policies On The Renewable Fuels Standard: Economic and Greenhouse Gas Implications." *Energy Policy* 56:5–15.

Hudiburg, T.W., S.C. Davis, W. Parton, and E.H. Delucia. 2015. "Bioenergy Crop Greenhouse Gas Mitigation Potential Under a Range of Management Practices." *GCB Bioenergy* 7(2):366–374.

Hudiburg, T.W., W. Wang, M. Khanna, S.P. Long, P. Dwivedi, W.J. Parton, M. Hartman, and E.H. DeLucia. 2016. "Impacts of a 32-billion-gallon Bioenergy Landscape on Land and Fossil Fuel Use in the US." *Nature Energy* 1(1):15005.

Khanna, M., and C.L. Crago. 2012. "Measuring Indirect Land Use Change with Biofuels: Implications for Policy." *Annual Review of Resource Economics* 4(1):161–184.

Parton, W.J., M. Hartman, D. Ojima, and D. Schimel. 1998. "DAYCENT and Its Land Surface Submodel: Description and Testing." *Global and Planetary Change* 19(1-4):35–48.

Plevin, R.J., A.D. Jones, M.S. Torn, and H.K. Gibbs. 2010. "Greenhouse Gas Emissions from Biofuels' Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated." *Environmental Science & Technology* 44(21):8015–8021.

Rajagopal, D. 2014. "Consequential Life Cycle Assessment of Policy Vulnerability to Price Effects." *Journal of Industrial Ecology* 18(2):164–175.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change." *Science* 319(5867):1238–1240.

Taheripour, F., and W.E. Tyner. 2013. "Induced Land Use Emissions due to First and Second Generation Biofuels and Uncertainty in Land Use Emission Factors." *Economics Research International* 2013:1–12.

United States Government. 2013. Technical support document: technical update of the social cost of carbon for regulatory impact analysis-under executive order 12866. Interagency Working Group on Social Cost of Carbon. Available at: https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf.

Zilberman, D., G. Hochman, and D. Rajagopal. 2011. "On the Inclusion of Indirect Land Use in Biofuel Regulations." *University of Illinois Law Review*:413–433.

Table 1. ILUC Factors Estimated by Various Studies

(gCO2/MJ)	Corn ethanol	Miscanthus ethanol	Switchgrass ethanol	Soybean biodiesel	Sugarcane ethanol	Corn Stover ethanol
EPA (2010)[1]	30.3 (19.9-43.6)		14.2 (8.5-21.8)	40.8 (14.2-72)	3.8 (-4.7-11.4)	
Taheripour and Tyner(2013)[2]	12.9 (12.9-22.6)	5.8 (5.8-32.3)	20.3 (20.3-74)			-1 (-0.9-1.6)
CARB (2014)[3]	19.8			29.1	11.8	
CARB (2009)[4]	30 (18.3-44.3)		18	42 (27-51)	46 (32.3-56.7)	
Hertel et al (2010)[5]	27 (14.7-90)					
Tyner et al (2010)[6]	(14.5-22.9)					
Searchinger et al (2008)[7]	104		111			
Dumortier et al (2009)[8]	(14-63)					
Plevin (2010)[9]	(21-142)					

[1] Environmental Protection Agency. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*. *Program* (2010). doi:EPA-420-R-10-006

[2] Taheripour, F. & Tyner, W. E. Induced land use emissions due to first and second generation biofuels and uncertainty in land use emission factors. *Econ. Res. Int.* **2013,** 1–12 (2013).

[3] California Air Resources Board (CARB). *Staff Report: Initial Statement of Reasons for Proposed Rulemaking*. (2014).

[4] California Air Resources Board (CARB). *Proposed Staff Report: Initial Statement of Reasons. Regulation to Implement the Low Carbon Fuel Standard.* (2009).

[5] Hertel, T.W.*et al.* Global Land Use and Greenhouse Gas Emissions Impacts of US Maize Ethanol: The Role of Market-Mediated Responses. BioScience 60: 223-231 (2010).

[6] Tyner, W.E. *et al.* Land use changes and Consequent CO2 Emissions due to US corn ethanol production: A comprehensive analysis. West Lafayette, IN, USA: Department of Agricultural Economics, Purdue university. (2010).

[7] Searchinger, T. *et al.* Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **319,** 1238–1240 (2008).

[8] Dumortier, J. *et al*. Sensitivity of Carbon Emission Estimates from Indirect Land-Use Change. Applied Economic Perspetives and Policy. 33(3),428-448 (2009).

[9] Plevin, R. J. *et al.* Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. *Environ. Sci. Technol.* **44,** 8015–8021 (2010).

Table 2. Values of Direct Biofuel Carbon Intensity And ILUC Factors Assumed in this Study for Alternative Scenarios

(gCO2/MJ)	**Carbon Intensity**	**ILUC Factors**		
		CARB	**EPA**	**Searchinger**
Corn Ethanol	56.7	19.8	30.3	104
Miscanthus Ethanol	-57.2	5.8[1]	14.2[2]	111[2]
Switchgrass Ethanol	-48.1	20.3[1]	14.2	111
Cornstover Ethanol	25.5	-1 [1]	-1 [1]	-1 [1]
Willow Ethanol	-22.5	0	0	0
Poplar Ethanol	-13.1	0	0	0
Energycane Ethanol	-18.1	0	0	0
Soybean Diesel	34.7	29.1	40.8	40.8[3]
Sugarcane Ethanol	26.1	11.8	3.8	3.8[3]

1 Taheripour, F. & Tyner, W. E. Induced land use emissions due to first and second generation biofuels and uncertainty in land use emission factors. *Econ. Res. Int.* **2013,** 1–12 (2013).

2. CI value of miscanthus is unknown and assumed to follow the estimated value of switchgrass

3. CI value is unknown and assumed to follow the EPA estimation

Table 3. Effect of Alternative Policies on GHG Emissions and Costs of Abatement

Scenario	**No_LCFS Baseline**			**LCFS_NO_ILUC Factor**			**LCFS_With_ILUC Factor**		
	CARB	EPA	**Search-inger**	**CARB**	**EPA**	**Search-inger**	**CARB**	**EPA**	**Search-inger**
US GHG Emissions (without ILUC) (B Mg CO2)	43.5			42.7 (-1.8%)			42.2 (-3.1%) (-1.3%)	42.1 (-3.1%) (-1.4%)	41.8 (-4%) (-2.2%)
US GHG Emissions (with ILUC) (B Mg CO2)	44.0	44.2	46.2	43.2 (-1.9%)	43.5 (-1.7%)	43.9 (-5.1%)	42.6 (-3.2%) (-1.3%)	42.8 (-3.3%) (-1.6%)	42.7 (-7.6%) -2.6%)
US GHG Emissions (with ILUC) and Rest of the World Gasoline Emissions (B Mg CO2)	89.1	89.4	91.4	88.27 (-0.9%)	88.6 (-0.9%)	89.0 (-2.6%)	87.7 (-1.6%) (-0.6%)	87.9 (-1.6%) (-0.7%)	87.9 (-3.8%) (-1.2%)
US Abatement Cost Relative to No_LCFS Baseline ($ Billion)				-34.9[1]			35.1	50.0	210.5
US Cost of Additional Global Abatement Due to ILUC Factor ($/Mg CO2)							63.7	76.6	196.9

The first row of numbers in parenthesis is percentage change relative to the No_LCFS Baseline scenario, and the second row of numbers is percentage change relative to LCFS_No_ILUC scenario.

[1] The negative abatement cost indicates that US economic surplus increased relative to the No_LCFS baseline.

Table 4. Effects of Alternative Policies on Economic Surplus Relative to a No LCFS Policy Scenario ($ Billion)

	No LCFS Policy	LCFS_NO_ILUC Factor	LCFS_With_ILUC Factor		
			CARB	EPA	Searchinger
Social Welfare ($B)		***Change Relative to No LCFS Policy: Cost of Abatement***[1]			
Fuel Producer	2258.6	12.4	0.3	-3.2	-125.5
Agricultural and Forestry Producers	1878.2	-67.0	-75.1	-78.0	-9.1
Total Producer's Surplus	4136.8	-54.6	-74.9	-81.3	-134.6
Fuel Consumers	19060.9	78.1	60.1	45.7	-97.6
Agricultural and Forestry Consumers	3327.6	11.0	13.6	19.4	55.6
Total Consumer's Surplus	22388.5	89.1	73.7	65.1	-42.1
Government Revenue	988.3	0.5	1.0	1.1	1.1
Total	27513.6	34.9	-0.2	-15.1	-175.6
Additional Cost Due to Inclusion of ILUC Factor			35.1	50.0	210.5

[1] Positive numbers represent a gain in economic surplus while negative numbers represent a loss.

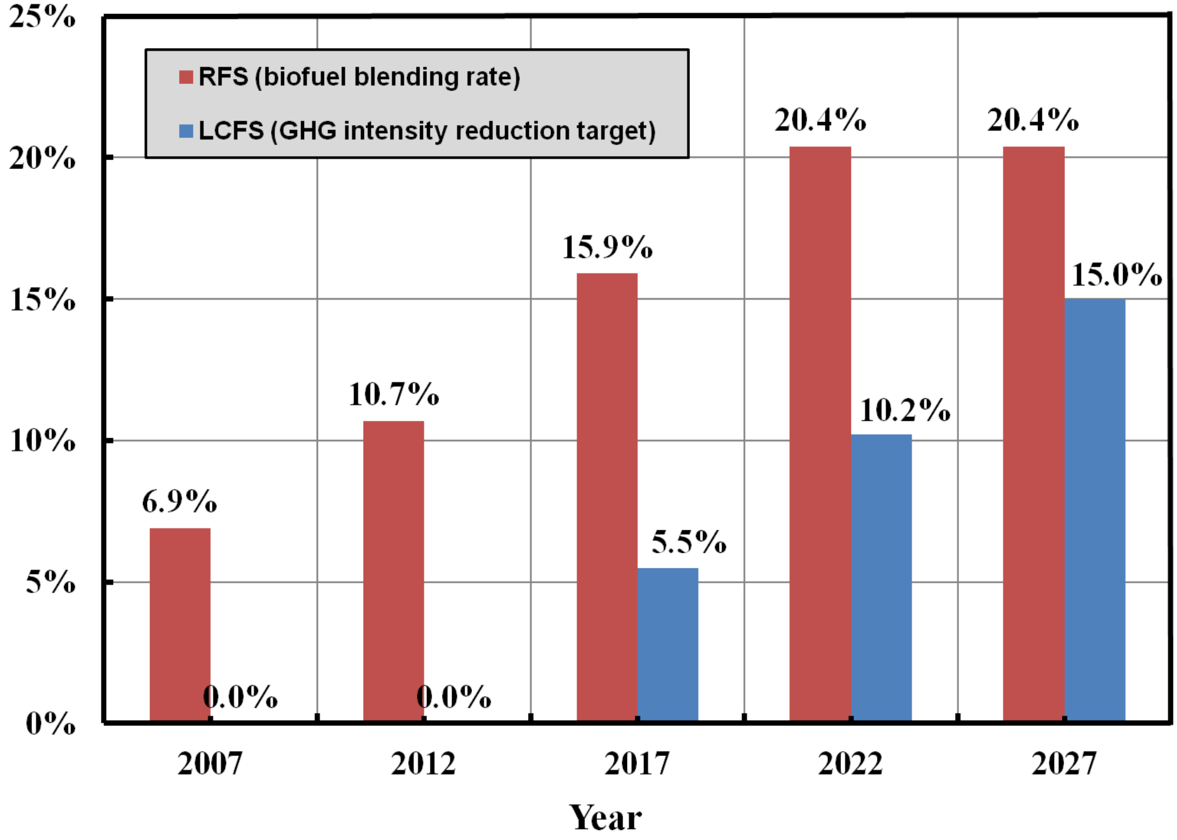

Figure 1. Policy Targets Assumed in this Study

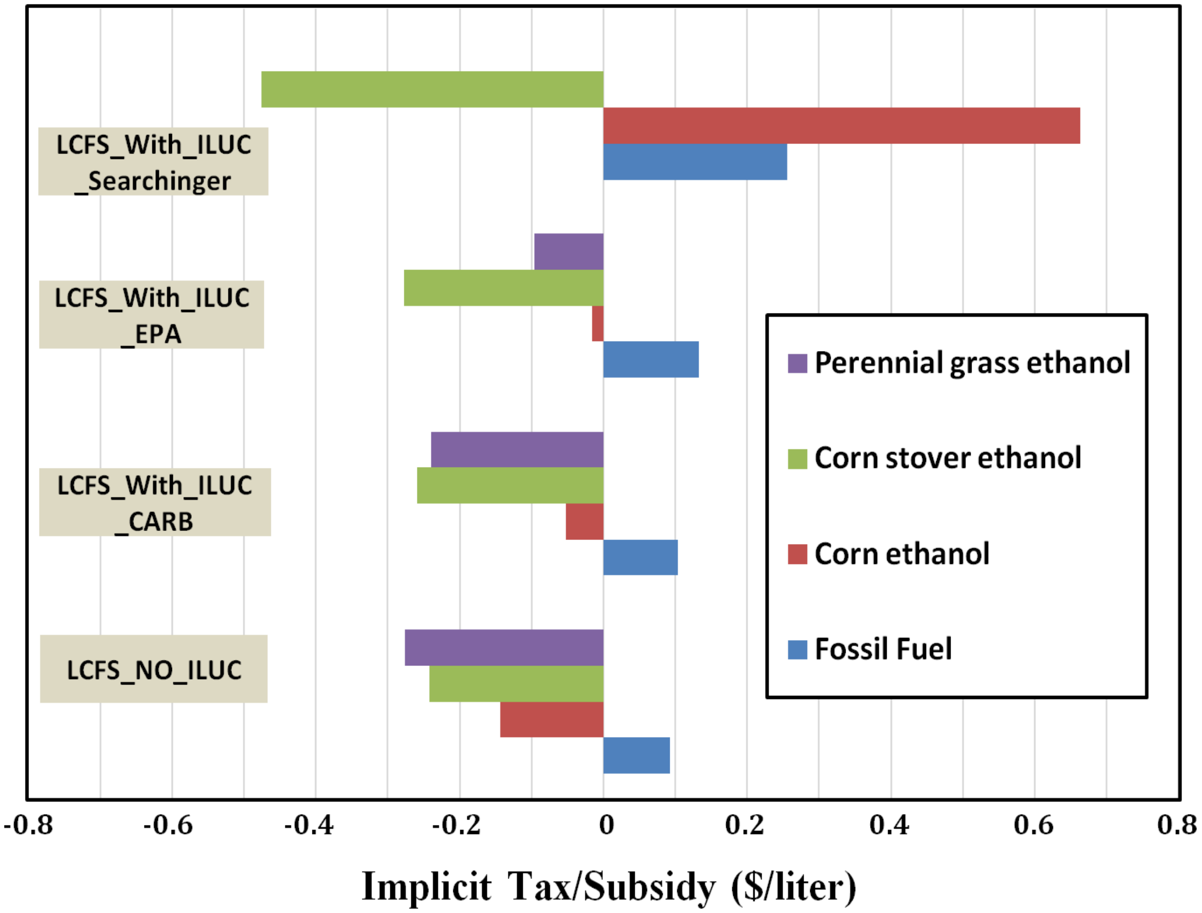

Figure 2. Implicit fuel taxes and subsidies with and without an ILUC factor

***** The positive values represent a tax while negative values represent a subsidy on the fuel.

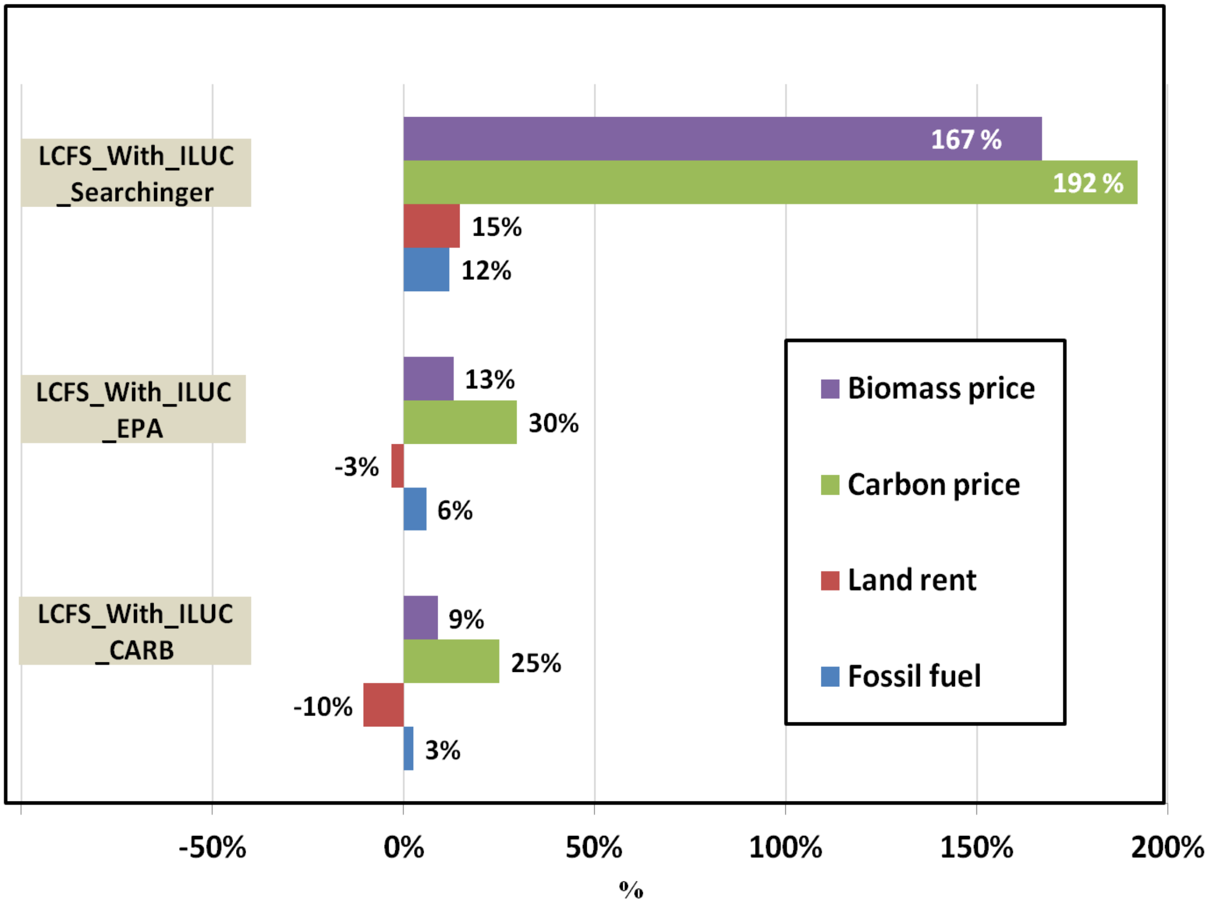

Figure 3. Change in fuel consumption in the LCFS_With_ILUC factors relative to the LCFS_No_ILUC factor scenario

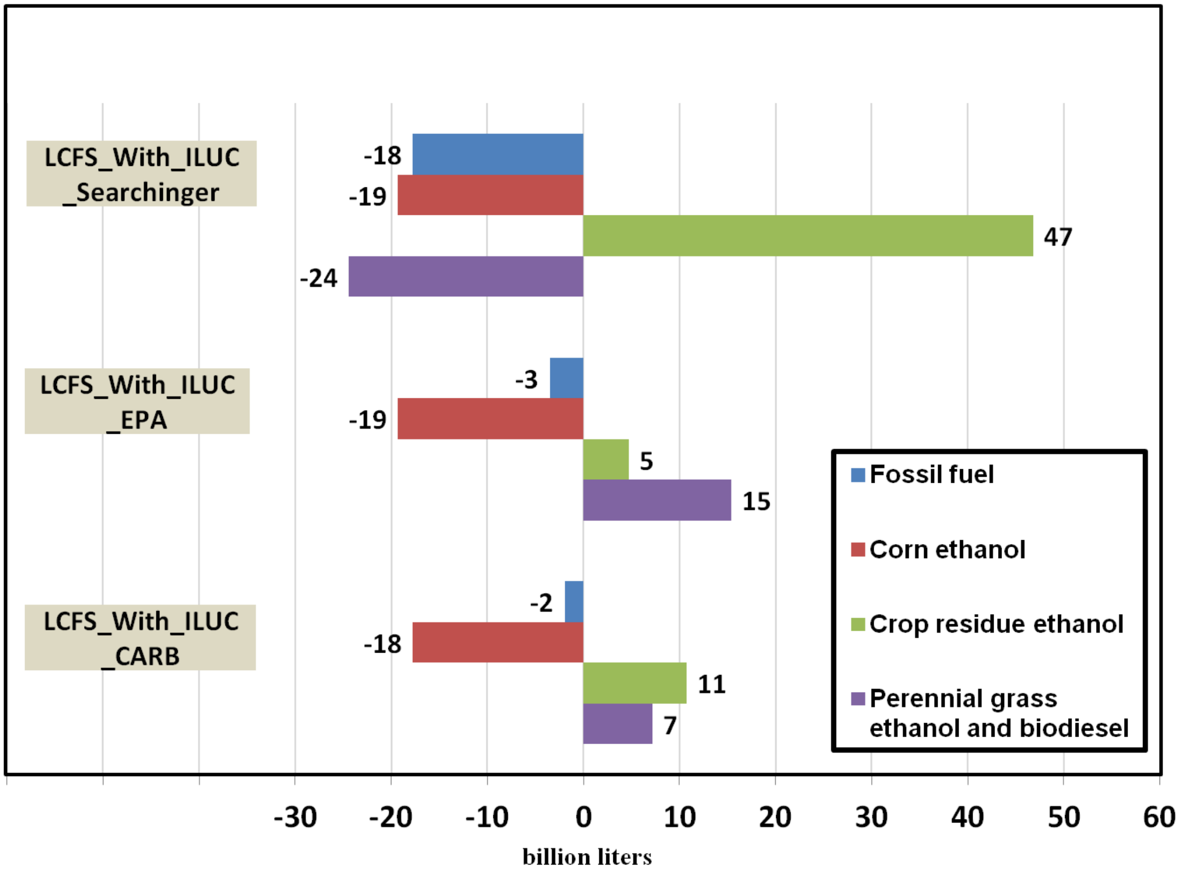

Figure 4. Change in fuel consumption in the LCFS_With_ILUC factors relative to the LCFS_No_ILUC factor scenario

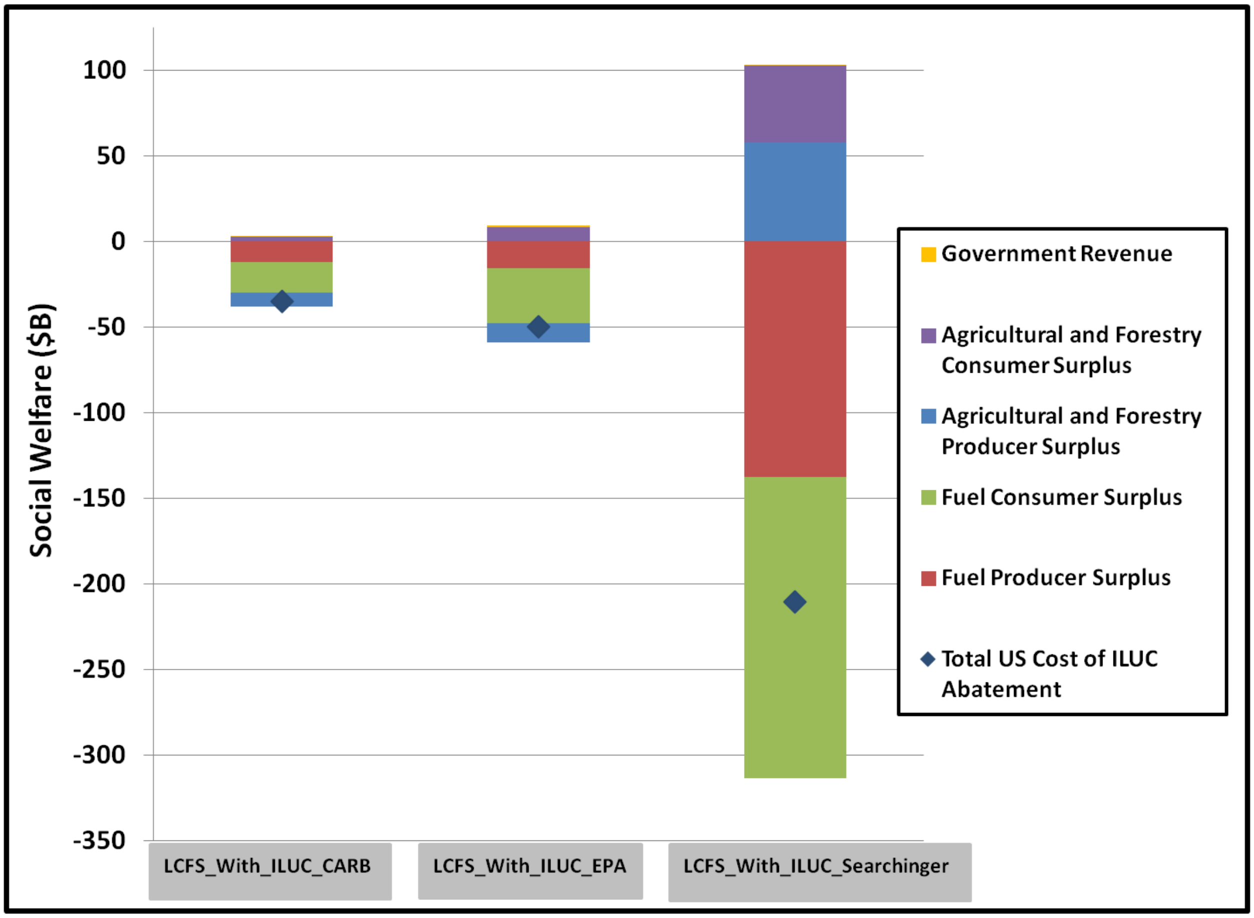

Figure 5. Effects of each ILUC factor (Searchinger, EPA, and CARB) on the discounted value of economic surplus (Social Welfare) relative to an LCFS_No_ILUC factor scenario

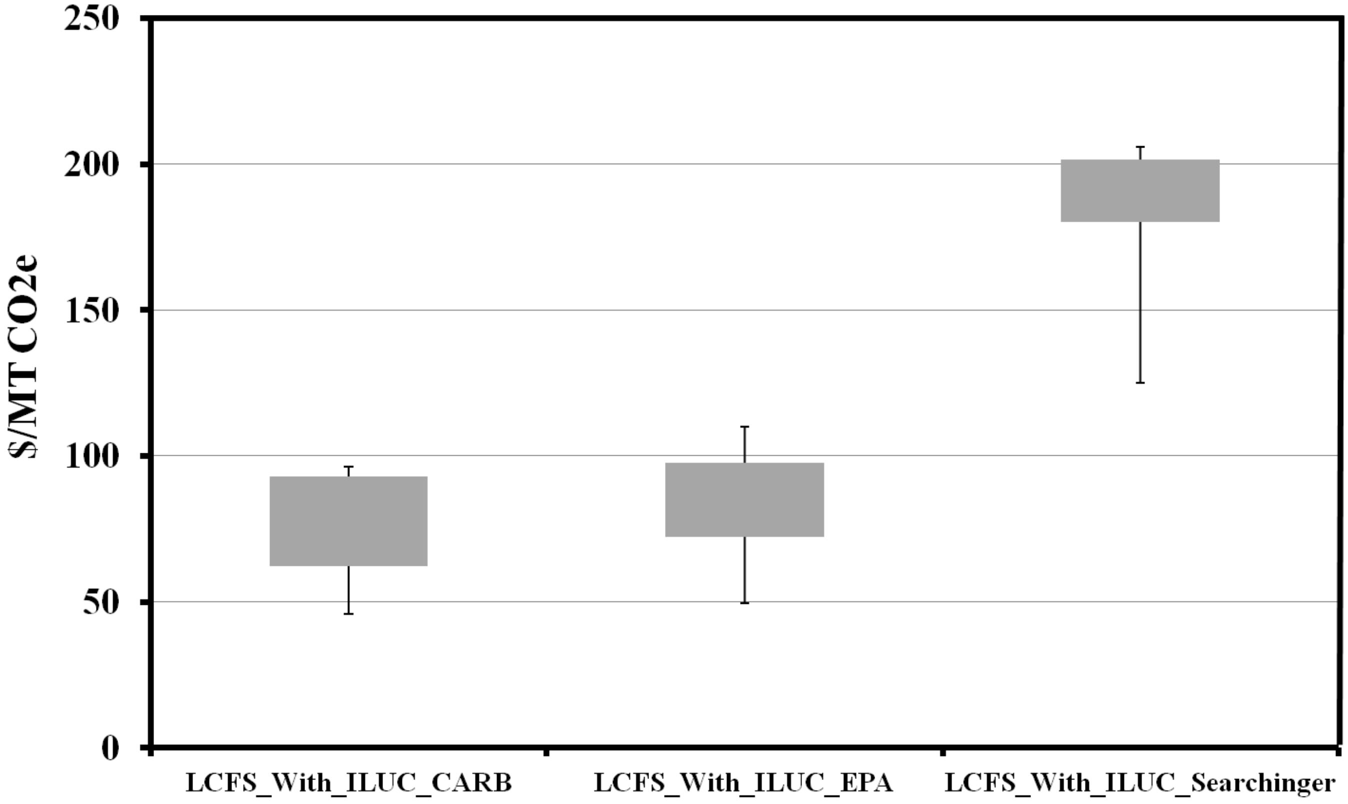

Figure 6. Sensitivity Analysis of the Additional US Cost of Abatement Due to the Inclusion of the ILUC Factor