

The Indirect Byproduct Effect of Biofuels

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Recent debates on the environmental benefits of biofuels have focused on the negative GHG effects of indirect land use change. In this paper we identify a heretofore unrecognized indirect effect of biofuels resulting from decreased supply of petroleum byproducts- the indirect byproduct effect (IBE). The IBE represents the change in GHG associated with the displacement of petroleum byproducts which are eliminated or replaced with reduction in transportation fuel. We derive a range of values to capture the order of magnitude of this effect and find that it is likely to reduce the GHG emissions associated with biofuels and thus serve to offset the negative effect of indirect land use changes. Stylized numerical analyses suggest that when the IBE is included in the LCA, corn-based ethanol easily meets minimum requirements for renewable fuel credits under the Renewable Fuel Standards.

At least since the 1900 World's Fair in Paris, when the Otto Company exhibited a small Diesel engine running entirely on peanut oil, biofuels have figured prominently in the hope for clean, renewable energy (1). However, the environmental benefits of biofuels have long been controversial (2). In a meta-analysis, Farrell *et al.* (3) finds that most analyses conclude corn-based ethanol delivers modest greenhouse gas (GHG) reductions compared to gasoline. In an influential article, Searchinger *et al.* (4) argues that when the indirect effect on land-use changes (ILUC) from increased corn production are considered, the modest GHG savings found in Farrell *et al.* are reversed. Although the Searchinger *et al.* estimates are among the highest in the literature, subsequent research confirms that indirect effects, and ILUC in particular, can dramatically influence the life cycle assessment (LCA) of biofuels (4, 5), generating practical

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implication for legislation (6). However, the inclusion of ILUC in LCA also suggests that other meritorious indirect effects should be considered (7).

Much of the discussion of indirect effects has centered on the consequences of increased biofuel production (4, 5, 8, 9), but there are indirect consequences to the corresponding decrease in gasoline and diesel production as well. Gasoline and diesel are derived from crude oil along with byproducts of the refining process, such as jet fuel, heating oil, liquid petroleum gases, petroleum coke, and asphalt. These petroleum “byproducts” (which account for roughly 1/3 a barrel of oil by volume) emit GHGs, and in most cases, at higher per unit rates than gasoline and diesel. Substituting biofuels for gasoline and diesel tautologically reduces gasoline and diesel supplies, but because of the multiproduct nature of petroleum refinery, it also indirectly reduces production of petroleum byproducts. The fall in petroleum byproduct supply affects GHG emissions, resulting in what we call the indirect byproduct effect (IBE) of biofuels. In this article, we derive a range of values for the IBE to assess the order of magnitude of this effect and compare to other components of LCA, most notably the ILUC. We then discuss the policy and environmental implications of including IBE in the LCA of biofuels in the context of the US Renewable Fuel Standards (RFS) adopted in March 2010.

The IBE depends on, among other factors, flexibility in refinery output. To accommodate increased biofuel production (from a government mandate, for example), the optimal response of a refinery, absent constraints, would be to decrease the share of gasoline and diesel produced from a barrel of crude oil, thus leaving the level of byproduct supply unchanged. With no change in byproduct levels, GHG emissions from byproducts would not change and the IBE would equal 0. However, refineries face significant technological constraints, suggesting that production in the short-run can be approximated with fixed-proportion coefficients (10-12).

Given this assumption, a biofuel mandate would displace gasoline and diesel and byproducts at the same rate.

The second main factor upon which the IBE crucially depends is the availability of substitutes for the different byproducts. Where alternatives do not exist or are prohibitively expensive, byproduct supply and GHG emissions will unambiguously fall. However, where alternatives exist, the sign of the IBE is ambiguous and will depend on the alternative chosen. For example, if biofuel production displaces heating oil, electricity-producing utilities may switch to coal, or natural gas, or even wind power. If utilities switch to natural gas or wind, GHG emissions fall because natural gas and wind are cleaner than heating oil. Conversely, if utilities switch to coal, then emissions increase. In some cases, the replacement from alternatives will be expensive, in which case there will only be partial replacement. For example, natural gas is more expensive than Liquid Petroleum Gas (LPG), so we would not expect a fall in LPG supply to be completely offset by an increase in natural gas consumption.

In general, the IBE will depend on the supply and demand of the nonpetroleum alternatives and refinery adjustment. Lacking reliable econometric estimates of these parameters, we instead calculate a range of values for the IBE corresponding to different simplifying assumptions regarding these market responses. The analysis allows us to access the order of magnitude of the IBE and compare to other LCA components to determine if including IBE in LCA could generate important policy implications (13).

We calculate the IBE under 4 scenarios. In the first two scenarios, we assume full replacement from viable alternatives. In these scenarios, the entire volume of displaced byproduct is replaced by an alternative, so the IBE is just the size of the displacement multiplied by the GHG emissions differential. In the last two scenarios, we assume no replacement from

alternatives. In these simulations, the IBE is calculated as the size of the displacement times the per unit GHG emissions of the byproduct. The assumption of full replacement generates a lower bound on the IBE, while assuming no replacement generates the upper bound.

Within each scenario couple described above, we then vary the assumption about refinery flexibility. In scenarios 1 and 3, we assume sufficient flexibility such that refineries increase the byproduct share to leave volume of byproduct unchanged, but assume this adjustment does not happen immediately. We assume the technology adjustment phases in over time in a linear fashion so that in the first year, there is no refinery adjustment (so byproduct displacement equals the size of the mandate), but after 30 years, the byproduct share increases such that by year 30, byproduct levels return to no-biofuel projected levels (14). Given that, historically, refineries have responded to changing market conditions with significant time lags, the assumption of linear adjustment is conservative. In scenarios 2 and 4, we assume a fixed byproduct share over time, so that in each year, byproduct displacement equals the size of gasoline displacement.

To calculate the IBE, we consider 8 final good markets corresponding to the end-uses of various petroleum byproducts: heating oil, jet fuel, asphalt, LPG, coke, still gas, residual fuel and other petroleum products. Heating oil and residual fuel are heavy fuel oils used for heating, shipping, and power generation. Viable alternatives for these petroleum byproducts include natural gas, wind, and coal. In the simulations that follow, we assume replacement comes from natural gas at per unit emissions differential of 20 g CO₂e/MJ and 0 g CO₂e/MJ, respectively (15). LPG and still gasses, such as butane and propane, are used for heating, cooling, cooking and producing plastics. We assume these petroleum byproducts are also replaced with natural gas at per unit emissions differentials of 10 g CO₂e/MJ and -10 g CO₂e/MJ, respectively. Petroleum coke is a carbonaceous solid derived from oil refinery coker units and is used for

heating and power generation and to make electrodes. We assume replacement from coal at a 0 g CO₂e/MJ differential. Asphalt, also known as bitumen, is a viscous liquid or semi-solid that is used in road construction. We assume the alternative to be concrete, which emits 32 g CO₂e/MJ less GHG than asphalt. Finally, we assume jet fuel and other petroleum products are replaced by biofuels at per unit emissions differentials of 21 g CO₂e/MJ and 11 g CO₂e/MJ, respectively.

For all 4 scenarios, we adopt the assumption and methods used by the EPA to calculate the LCA of different biofuels, namely 1) the biofuel shares increase from 6% in 2009 to 18% in 2022 in compliance with the RFS 2) the GHG calculation period starts in 2022 and is amortized over 30 years at 0% discount rate (16). We sum over all 8 markets to calculate total GHG emissions saving from petroleum byproducts associated with the mandate (17). To convert this figure to a per MJ reduction associated with a specific biofuel, we note that a given quantity of any gasoline or diesel substitute will generate the same GHG savings from byproducts, since the savings depend only on the reduction of gasoline or diesel, not on the manner in which the gasoline or diesel is replaced. Thus, we can attribute GHG savings from any biofuel included in the mandate by dividing the total GHG savings by the volumetric share of that biofuel in the mandate. We then divide this number by the total energy content of that biofuel, yielding an emission rate in gCO₂e/MJ associated with that biofuel. We include the IBE in the EPA's LCA for corn-based ethanol produced from a natural gas plant in scenarios 1-4 (relative to gasoline) and report the results in Figure 1 (14, 18).

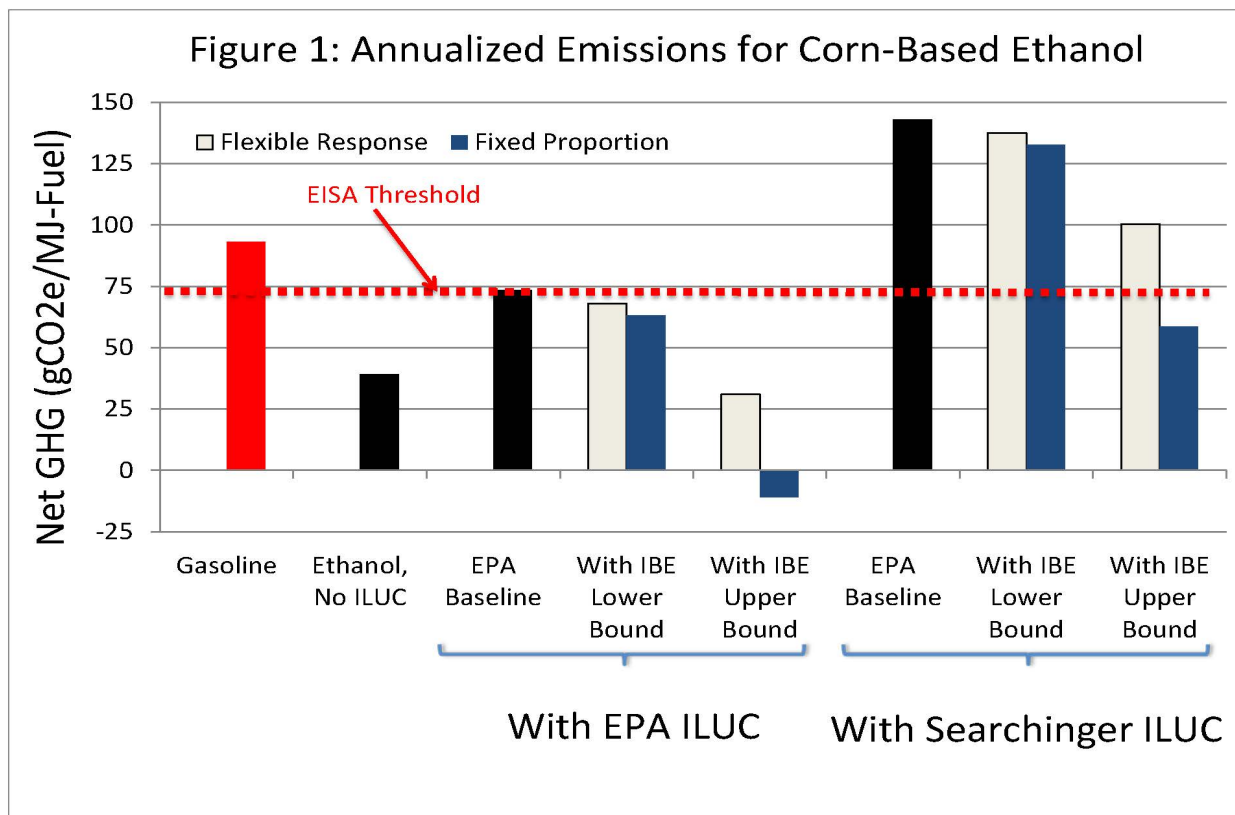
Moving to the results from our simulations, we find that without including ILUC (19), the EPA calculates the annual emission of corn-based ethanol to be 39 gCO₂e/MJ, compared to 92 gCO₂e/MJ annual emissions for gasoline (first two columns of Figure 1). When the EPA includes ILUC, it calculates corn-based ethanol emits 74 gCO₂e/MJ per year, which represents

21% less GHG emissions than traditional gasoline (column 3 of Figure 1). This is the official EPA calculation (what we call EPA “baseline”) used to justify the renewable status of corn-based ethanol. Notice that the EPA baseline calculation implies corn-based ethanol barely surpasses the EISA minimum emissions reduction threshold of 20%. By contrast, including IBE in the EPA's LCA (with ILUC), we find in columns 4-5 that corn-based ethanol emits between -11 and 68 gCO₂e/MJ, which represents between 27% and 112% less GHG emissions than traditional gasoline, depending on the assumption about replacement and adjustment. Clearly, the different cases present a wide range of possible outcomes, but even the lower bound estimates suggest that including IBE in the LCA of corn-based ethanol can partially offset the effects of ILUC, increasing the emissions savings of corn-based ethanol from 21% to 27%. The midpoint of the two bounding cases would imply GHG savings of 40 gCO₂e/MJ, which is larger in magnitude than the increase in emissions associated with ILUC.

While direct comparison to the EPA numbers is informative, it is also important to compare the IBE to higher estimates of ILUC as well, since the literature on ILUC has produced a range of estimates (5). We will use the Searchinger *et al.* numbers as our benchmark, which are roughly 3x the size of the EPA estimates (9). Using the Searchinger *et al.* estimates, without including IBE, corn-based ethanol emits 143 gCO₂e/MJ, or 54% *more* GHGs than gasoline (column 6). Including the IBE upper bound estimate, corn-based ethanol emits 58 gCO₂e/MJ (column 8), which again puts corn-based ethanol within the EISA requirement of 20% reduction compared to gasoline. This analysis suggests that for the upper bound case, even using the controversial Searchinger *et al.* ILUC estimates, corn-based ethanol can meet EISA standards if one considers the IBE.

The LCA-based GHG emissions of fuels guide policy makers when developing climate change policy. Our analysis demonstrates that these emissions depend, not only on motor fuel products (gasoline and diesel), but on the petroleum byproducts as well. Although the environmental impacts of decreased petroleum byproducts is uncertain and depends on refinery flexibility and alternative substitutes, our analysis suggests that the GHG reductions from the IBE could be large and have direct policy implications: without considering IBE, the EPA's LCA-based GHG emissions calculation of corn-based ethanol indicates that this fuel barely qualifies as a renewable fuel (and actually fails to meet the minimum requirement under some assumptions), while including IBE in the LCA leaves corn-based ethanol well within the emissions range of a renewable fuel. The analysis suggests that if indirect effects are considered in biofuel policies, ignoring the IBE may lead to underestimation of the contribution of biofuels to GHG emissions reductions.

While first-generation biofuels like corn-based ethanol represent the only biofuels that are currently commercially viable, it is the hope of many that second- or even third-generation biofuel feedstocks such as miscanthus or algae will eventually supplant first-generation fuels. The feedstock for these later-generation biofuels offer significantly higher yields and do not compete with the food supply, which means the indirect effects on land-use change will be much smaller. However, the IBE on GHG reductions is the same regardless of the biofuel technology replacing gasoline and diesel, which suggests that later-generation biofuels may carry even larger environmental benefits than are currently believed.



Notes: LCA calculations for gasoline and corn-based ethanol produced from a natural gas plant using EPA methodology and including different indirect effects. EISA threshold indicates the implied maximum acceptable LCA for a renewable fuel under the RFSII (20% less than traditional gasoline). IBE lower bound corresponds to full replacement scenario, while IBE upper bound corresponds to no replacement. EPA baseline includes ILUC but no IBE.

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[13] In future work, we plan to calculate the IBE more precisely using econometric estimates of supply and demand elasticities.

[14] Materials and methods are available as supporting material on *Science* Online.

[15] The emissions intensity figures are LCA estimates (14).

[16] EPA Renewable Fuel Standards (March 2010). At <http://www.epa.gov/otaq/fuels/renewablefuels/index.htm>

[17] We consider the joint effect of all biofuels included in the mandate because it is the total displacement of gasoline and diesel that will drive refinery adjustment and because the EPA follows this non-attributional approach as well (14).

[18] We focus our analysis on corn-based ethanol because that is the biofuel with the largest market share and because much of the controversy regarding GHG emissions potential of biofuels has centered on corn-based ethanol (2-9).

[19] These are just the international land use change estimates. The EPA does not breakout ILUC (international + domestic) as a distinct category in their LCA calculation.

Supporting Online Materials

Materials and Methods

Tables S1 to S2

Fig. S3 to S4

References

