ON THE INDIRECT EFFECT OF BIOFUEL

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Biofuel policies were partially motivated by concerns about climate change. Therefore, qualifications for the benefit of these policies were based on the amount of greenhouse gas emissions (GHGE) of particular biofuels. For example, entitlement for subsidies and mandates associated with the U.S. Energy Independence and Security Act of 2007 requires remaining below upper bounds of GHGE per gallon. The computation of the GHGE of biofuel are based on lifecycle analysis (LCA), which takes into account emissions throughout the supply chain, including fertilizer production and use, shipping, and refining. Searchinger et al. (2008) introduced the indirect land use change (ILUC) of biofuel production, which is the extra GHGE resulting from the expansion of acreage of a feedstock such as corn to accommodate the increase in price associated with the introduction of biofuel. Governments have considered including ILUC in computing GHGE of various biofuels to determine compliance with policies like the Renewable Fuels Standard (RFS) or Low Carbon Fuel Standard (LCFS). Thus, inclusion of the ILUC in the computation GHGE of a fuel will make it more difficult to qualify for the RFS. This paper identifies some of the challenges associated with the application of LCA, and in particular, the use of ILUC as part of the estimated GHGE of biofuel.

Economists have found that LCA has multiple flaws (Khanna and Crago 2012) in current biofuel polices and many have reservations about the use of LCA as a major regulatory tool. But accepting that LCA is used for regulation, our challenge is to use economic analysis to evaluate the use of ILUC in computing the GHGE of biofuel in the policy process. In the next section we develop an economic foundation for the computation of ILUC and derive a related indirect effect—the indirect food consumption effect (IFCE) of biofuels. This is followed by the discussion of other indirect effects. The third segment investigates the reliability of ILUC estimates and their use in the regulatory process, which is followed by a conclusion.

Conceptual Analysis of the Use of LCA in Computing GHGE of Biofuels

To better view the LCA of GHGE of biofuel from an economic perspective, we will develop a simple conceptual model. Let B denote the amount of a biofuel we analyze. LCA considers the GHGE resulting from the production of B units of biofuel throughout the supply chain. Assume that biofuel production includes two stages: production of feedstock and processing used to produce the biofuel. The GHGE generated in producing the biofuel can be decomposed into (1) the emissions from the production of the feedstock denoted by GF and (2) emissions from processing denoted by GP. The calculation of the GHGE of the feedstock GF considers the GHGE of activities both on the farm (use of tractors and other machinery) and off the farm (production of fertilizers). LCA is seeking to calculate impact coefficients based on average performance that will enable the assessment of the annual GHGE associated with a proposed

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This article was presented in an invited paper session at the 2013 ASSA annual meeting in San Diego, CA. The articles in these sessions are not subjected to the journal's standard refereeing process.

Amer. J. Agr. Econ. 95(5): 1332–1337; doi: 10.1093/ajae/aat038

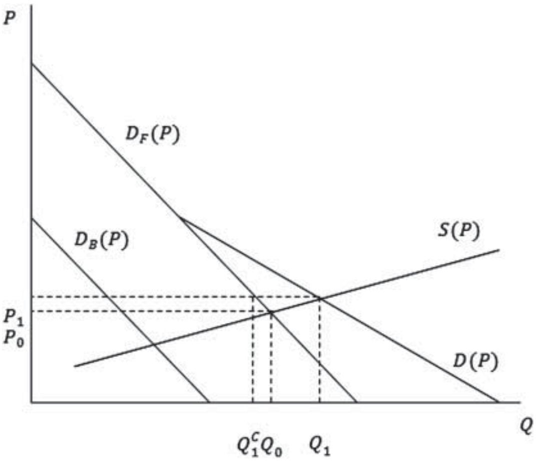

Figure 1. The equilibrium with and without biofuel

plant. Thus, the direct effect coefficient of biofuel is denoted as $I_D = (GF + GP)/B$.

Searchinger et al. (2008) emphasizes the importance of including the ILUC of biofuel production in the LCA assessment. The ILUC is the increase in GHGE from land allocated to crop production in response to the increase in prices of these crops resulting from diversion of some of their output to biofuel production. For simplicity, we will derive the ILUC analytically for one crop.

Let ΔG_{IL} denote changes in GHGE associated with changes in land use resulting with the production of B units of biofuel. Assuming that production of each unit of biofuel requires γ units of feedstock, the amount of feedstock utilized in producing B units of biofuel is γB. We will solve for the ILUC coefficient denoted by $I_{IL} = \Delta G_{IL}/B$ using a partial equilibrium framework where the coefficient can be derived by solving for the price change in the feedstock market as well as the associated changes in land use and GHGE. Let the supply of a feedstock be denoted by $Q = S(P)$ and the demand for food as $Q = D_F(P)$. The initial level of the feedstock before the introduction of biofuel is Q_0 and the initial price is P_0 (see figure 1). The introduction of biofuel adds a demand for feedstock $Q = D_B(P)$ and the joint demand has two segments, represented by $Q = D(P)$. The introduction of biofuel results in a new equilibrium, where the feedstock price is $P_1 = P_0 + \Delta P$, where ΔP is the price change, total production is Q_1, the consumption of feedstock for food is $Q_1^C = D_B(P)$, and the amount of feedstock used for biofuel is $Q_1^B = Q_1 - Q_1^C = \gamma B$. The change in total feedstock is $\Delta Q = Q_1 - Q_0$ (see figure 1).

Searchinger et al. (2008) recognized that the per unit GHGE of feedstock may vary with the size of total production. Feedstock produced on lands used initially may have lower GHGE per unit of biofuel than biofuel produced at the extensive margin. To better understand ILUC, the supply after the introduction of biofuel can be decomposed into two elements. The first is corn produced on the lands used initially $A_0(\mu_0 + \Delta\mu(P))$, where A_0 and μ_0 are the initial acreage and yield per acre, respectively, and $\Delta\mu(\Delta P)$ the increase in yield per acre as price increases above P_0. The second is the new production on the extensive margin, namely, corn produced on land added following the introduction of B and the rise in the feedstock price, which is $A_E(\Delta P)\mu_E(\Delta P)$, where $A_E(\Delta P)$ is acreage of the extensive margin and $\mu_E(\Delta P)$ yield per acre of the extensive margin[1]. Thus at the new equilibrium:

$$(1) \qquad D(P_0 + \Delta P) + \gamma B = A_0(\mu_0 + \Delta\mu_0(\Delta P)) + A_E(\Delta P)\mu_E(\Delta P).$$

The change in output price after the introduction of biofuel can be solved from equation (1), which allows solving for the changes in land use and then in GHGE. The ILUC is the GHGE of the feedstock produced at the extensive margin $\Delta G_{IL} = g_E A_E(\Delta P)\mu_E(\Delta P)$, where g_E is the GHGE per unit of corn produced on the extensive margin, and thus the ILUC coefficient is

$$(2) \qquad I_{IL} = g_E A_E(\Delta P)\mu_E(\Delta P)/B.$$

The ILUC is only part of the increase in the GHGE from farming following the diversion of γB units of feedstock to biofuel. The incremental change in GHGE associated with the farming of the extra feedstock after the introduction of biofuel is

$$(3) \qquad \Delta G_F = \Delta G_{IL} + \Delta G_{IM}$$

where ΔG_{IL} is the change in GHGE due to ILUC and the intensive margin GHGE (IMG) effect is denoted as $\Delta G_{IM} = g_{IM} A_0 \Delta\mu_0(\Delta P)$ and is the increase in GHGE because of

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[1] Note $A_0(\mu_0 + \Delta\mu_0(\Delta P)) + A_E(\Delta P)\mu_E(\Delta P)$ is constructed so it is equal to $S(P_0 + \Delta P)$ *for* $P > P_0$.

intensification on the initial land, where g_{IM} is the GHGE per unit of corn produced on the intensive margin. In terms of figure 1, ΔG_F is the GHGE of the $Q_1 - Q_0$ units of incremental output after the introduction of biofuels.

The traditional LCA aims to compute the GHGE of all of the feedstock allocated to biofuels without considering market mediated adjustments of the GHGE resulting from the introduction of biofuel. Therefore, it will compute the GHGE of the $B = Q_1 - Q_1^C$ units of feedstock allocated to biofuel, which includes the GHGE of $Q_1 - Q_0$ feedstock incremental feedstock units and $Q_0 - Q_1^C$ feedstock units that were switched from producing feedstock for food to feedstock for biofuel. But these "switching" feedstock units did not contribute any extra GHGE and are therefore not included in the economic calculation of the incremental contribution of biofuel to GHGE. The modified LCA approach that incorporates ILUC recognizes the impact of market mediated adjustments in an asymmetric manner—the biofuels are credited for market mediated incremental GHGE because of land expansion but are not credited for a market mediated effect that reduced the GHGE of food production. Thus, if market mediated effects are incorporated in LCA, they should include not only ILUC, but also the indirect food consumption effect (IFCE).

How big is the IFCE? Here we present a conservative estimate. The direct effect of the LCA assumes that, on average, each unit of feedstock is emitting g_B units of GHGE, so the total direct effect of farming is $GF = g_B \gamma B$. Since the emissions from consumption, assuming the IFCE is $g_b \gamma Q_1^c$, the total impact of a change in B is $dg_b Q_1^c/dB = g_b dQ_1^c/dB$. Thus, we estimate the IFCE to be the proportional decline in the consumption of food due to the market mediated effect caused by introducing biofuel. Using the formula derived in appendix A of Rajagopal et al. (2007) for $dP/d\gamma B$, we derive the marginal reduction in food consumption in response to the increase in feedstock allocated to biofuel.

$$\frac{dQ_1^C}{d\gamma B} = \frac{dQ_1^C}{dP}\frac{dP}{d\gamma B} \cong -\frac{\partial D(\bullet)}{\partial P}\frac{1}{\varepsilon_D - \varepsilon_S}\frac{P}{Q} = -\frac{\varepsilon_D}{\varepsilon_D - \varepsilon_S} \tag{4}$$

Equation (4) suggests that when the elasticities of food demand and feedstock supply are constant, the IFCE is a fraction of the GHGE caused by farming activities. In this case, I_{IFC} is the measure of reduction in GHGE per unit of biofuel because of the IFCE. Thus, $I_{IFC} = -\varepsilon_D/(\varepsilon_D - \varepsilon_S)GF$. Farrell et al. (2006) suggested that 40% of the direct effect of GHGE of biofuel are associated with biofuel production. As we will argue below, the elasticity of supply varies significantly over time. In some periods, for example following breakthrough discoveries or when new frontiers are opened, it may be quite significant. During periods of low productivity growth it may be close to zero. So the IFCE may vary between values close to zero to anywhere below 40% of the direct effect. When the elasticities of demand and supply of the feedstock are equal, the IFCE is 20% of the direct effect. Note that when the IFCE is close to its limit, the ILUC is very small, since these periods are periods of limited supply expansion. These are periods when there is concern about food price effects of biofuels and less about its environmental impact. But when the IFCE is very small, the ILUC is not necessarily at its peak. A high IFCE may correspond to periods of expansion of supply at the intensive margin, namely, periods of increased productivity. Thus, there may be periods when the ILUC is substantial and the IFCE is low. Mundlak (2011)'s historical analysis of agricultural productivity suggests that these periods are infrequent since most of the growth in agricultural supply resulted from intensification.

Other Indirect Effects

The introduction of ILUC into LCA opened the door to considerations of other indirect effects of biofuel mitigated by markets or other factors. In particular:

1. Indirect coproduct effect (ICE; Barrows, Hochman, and Zilberman 2012). Fossil fuels are derived from oil with other coproducts with a fixed proportion technology, at least in the short run, and introducing changes in the ratios of these different coproducts is costly and time-consuming. The production of these coproducts is often associated with higher GHGE than gasoline or diesel. Reduction in the demand for gasoline or diesel due to being replaced by biofuel is likely to reduce the profitability of refining oil and thus reduce the amount of coproducts

produced at the refinery. These coproducts will be replaced, to some extent, and if the rate of replacement is relatively low or if they are replaced by products with lower GHGE, then the ICE is negative. On the other hand, if they are replaced by products that are GHGE intensive, the ICE is positive. Barrows, Hochman, and Zilberman (2012) found that the GHGE reductions from the ICE could be large and have direct policy implications. Without considering the ICE, the EPA's LCA-based GHGE 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 ICE in the LCA leaves corn-based ethanol well within the emissions range of a renewable fuel.

2. Indirect fuel use change (IFUC; Rajagopal, Hochman, and Zilberman 2011).[2] Introduction of biofuel is likely to affect the price of fossil fuels, which will affect GHGE. The sign of the IFUC is positive or negative depending on whether the consumption of fossil fuel after the change is greater or lesser than the initial consumption minus the amount replaced by biofuel (in energy terms). Thus, the IFUC is positive if the price of fossil fuel after the introduction of biofuel is sufficiently low. The IFUC is likely to be negative if the introduction of biofuel is imposed through a standard and the cost of biofuel is high while the IFUC tends to be positive and increase overall GHGE if the biofuel production is subsidized and its marginal cost is low.
3. Indirect OPEC effect (Hochman, Rajagopal, and Zilberman 2011). The oil sector is dominated by a cartel of nations, the Organization of the Petroleum Exporting Countries (OPEC), which uses its monopolistic power to maximize the welfare of its exporting members. This results in a significant wedge between the price of fuel in OPEC countries versus oil-importing countries. The biofuel sector is a competitive fringe, and when it introduces supply it tends to reduce overall fuel availability and prices. OPEC responds to fuel supply expansion due to biofuel by reducing its own supply to keep prices higher, which leads to reduced GHGE. Hochman, Rajagopal, and Zilberman (2011) found that under plausible assumptions, the OPEC effect is substantial and negative.

Further research is needed to develop a comprehensive framework that integrates all of these effects. For example, the IFUC and the OPEC effect are mutually exclusive. The ICE has a secondary element that is affected by the IFUC. Moreover, these are not the only indirect effects associated with the introduction of biofuel, so once the inclusion of indirect effects becomes part of the regulatory process, it is likely to proliferate to the delight of economists, but the transaction costs associated with it can be quite substantial. Our policy challenge is to develop mechanisms to include only a few considerations that are sound methodologically, are of a significant order of magnitude, and can be implemented rigorously.

The Challenge of Computing ILUC

There is a large body of literature aiming to estimate ILUC for corn ethanol, sugarcane, and other biofuels. Khanna and Crago (2012) analyze the challenges of facing these empirical studies and the alternative approaches these studies pursue. The ILUC may be distributed across continents, occur with significant time lags, is affected by various agricultural policies and trade regulations, and cannot be easily distinguished from other factors that affect land use changes (Khanna and Crago 2012). ILUC is computed using various partial equilibrium and computable equilibrium models. Some partial equilibrium models may be region specific and use data in high levels of detail that allows for the incorporation of spatial variations and dynamic considerations, while CGE models operate with a high degree of aggregation. A key challenge in computing ILUC is recognizing heterogeneity in land characteristics that will affect where and when production is expanding. There is a big difference in the GHGE as a result of farmland expansion when it originates from deforestation versus double cropping. Existing models have limited capacity to address these differences, reducing the reliability of their predictions. Furthermore, different assumptions regarding ease of

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[2] This notion is close to the notion of indirect output use change (Drabik and de Gorter 2011).

substitution of land use among use categories, the rate of change in agricultural productivity, and consumer demand result in widely varied GHGE estimates. Models that allow higher degrees of substitution among crops and alternative land use are likely to result in a higher ILUC, while models that allow for a higher rate of response in the intensive margin are likely to have a lower ILUC. Not surprisingly, there is significant variability among estimates of the ILUC of biofuels. For example, Hertel et al. (2010) estimated that the ILUC of corn ethanol is one quarter of the initial estimate of Searchinger et al. (2008), and Tyner et al. (2010)'s model found it to be one half of Hertel et al. (2010)'s estimate. Khanna and Crago (2012) illustrated similar and even larger variations in ILUC estimates in other crops. There is limited quantification of the plausibility of various assumptions, thus assessment of the reliability of outcomes is difficult.

Various elasticities are the key parameters of many of the models, but they may not be stable over time. Zilberman, Hochman, and Rajagopal (2011) showed that the decadal average of elasticities of agricultural acreage with respect to agricultural output (indicating how much acreage will increase globally with increased production) vary drastically among crops, countries, and decades. For example, during the 1960s and 1980s in the United States and in the 1990s in the rest of the world, higher wheat production was associated with a *reduction* of total acreage, while in other periods increased output was associated with large increase of acreage. Variations of these elasticities reflect the randomness of discoveries, policies, and economic conditions, which affect both changes in output and land use levels. This suggests that differences among ILUC coefficients do not only reflect *uncertainty* of estimates but basic inherent randomness and even *instability* of the coefficients. The variability of the elasticity of land with respect to output emanates from the historical variation of agricultural productivity over time, with periods of high productivity growth as well as stagnation (Federico 2009).

One research challenge is to capture the inherent variability of ILUC effects. Another challenge of ILUC research is to statistically assess the quality of the predictions made by ILUC studies, which are frequently utilized in policy making. For example, it is not clear to what extent the introduction of biofuel resulted in the high degree of deforestation and GHGE as was predicted by some studies (Nassar et al. 2011). A major problem of ILUC studies is that they tend to rely on models that were designed to compute annual allocation of land among crops based on static profit-maximizing decision making while decisions about deforestation can be long-term and dynamic. Deforestation happens sporadically and the use of repeated annual models to analyze choices that occur infrequently may result in misleading outcomes. The increase in commodity prices is only one factor leading to deforestation. The motivation for deforestation may be the return from wood (Brazil has two large pig iron mills in the Amazon that rely on wood for feedstock) as well as the need to establish property rights. While there are approximately 50 million hectares of cropland in Brazil, another 320 million hectares are available for agriculture, so the linkage between agricultural expansion and deforestation is not very obvious.

Guilhoto and Ichihara (2010) suggest that historically the Brazilian government provided massive incentives to encourage settlement in the middle of the country. But government policies, international agreements, and international mechanisms, such as Reducing Emissions from Deforestation and Degradation, can also slow and reverse deforestation, as has occurred recently in Brazil (Hochstetler and Keck 2008). Cochrane (1993) argues that historical evidence suggests that countries tend to settle their land base first and then increase agricultural productivity through intensification. In the United States, agricultural acreage reached its peak in 1920 even though output has increased twelvefold since then. Furthermore, agricultural production globally has tripled since 1950 while acreage has increased by only 25% (Federico 2009). Mundlak's (2011) assessment of agricultural productivity suggests that this can be mostly attributed to intensification and substitution of capital for acreage. The predictions made by short-term models that expect high rates of expansion of agricultural land and deforestation in response to the introduction of biofuel, which occupies a relatively minor share of land resources, seem doubtful in light of this historical evidence, putting into doubt the large impacts predicted by some ILUC estimates.

Conclusion

Concern for the environment due to the impact of biofuel led to the inclusion of ILUC in LCA, but once included, other indirect effects should be considered as well. Our analysis suggests that in addition to statistical difficulties in estimating indirect effects, their behavior is very unstable over time. Thus, with the current state of knowledge, the inclusion of indirect effects in biofuel regulation is of questionable value, and we are challenged to better quantify these effects. Furthermore, the recent article by Rajagopal and Plevin (forthcoming) argues that inclusion of ILUC in partial (not global) biofuel policies (like the U.S. RFS) is not likely to reduce overall GHGE because of lower fuel prices in countries that do not introduce these polices. They also find that the lower the direct LCA of biofuel, the lesser the importance of the indirect effects. Thus, if the use of biofuel standards with the aim of reducing GHGE continues, introducing stricter regulatory targets gradually in order to provide incentives to reduce the direct effect of biofuel will increase the likelihood of reducing GHGE over time.

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