Lessons Learned from U.S. Experience with Biofuels: Comparing the Hype with the Evidence

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Abstract

Biofuel production in the United States, primarily from corn, has more than doubled since 2007, leading to concerns about its unintended consequences on agricultural and fuel markets. To examine the validity of these concerns and inform the debate about biofuels and their impacts, we review ex-ante projections and ex-post evidence of the effects of biofuels on land use, food and fuel prices, and greenhouse gas emissions. We find that the biofuels expansion contributed to an initial significant increase in agricultural commodity prices, but these impacts have dissipated over time as crop productivity has increased and cropping patterns have changed. Simulated estimates of indirect land use change and related greenhouse gas emissions intensity of biofuels have also declined sharply from their early levels, which is consistent with ex-post evidence. Additionally, growth in biofuel production caused a very modest reduction in fossil fuel prices, implying a small fuel rebound effect. Overall, estimates imply that first-generation biofuels from corn have a lower carbon intensity than gasoline. Finally, learning-by-doing, economies of scale, and technological improvements have made biofuels from corn increasingly competitive, reducing the need for subsidies and import tariffs. We conclude with a discussion of the lessons learned from the U.S. biofuels experience.

INTRODUCTION

There has been a rapid expansion in the global production of first-generation biofuels from food crops in recent decades. The United States and Brazil are currently the world's two largest producers of ethanol[1] and account for about two-thirds of global ethanol production.[2] Biofuels are produced primarily from corn in the United States and sugarcane in Brazil. U.S. corn ethanol production has more than doubled since 2007, and in 2010, it overtook Brazil as the world's largest ethanol producer. Policies to support biofuels in the U.S. have been driven primarily by the objective of increasing energy security and reducing dependence on foreign oil, but they have also sought to mitigate greenhouse gas (GHG) emissions from transportation fuel consumption and to enhance rural economic development.[3]

The initial positive view about the potential for biofuels to achieve these objectives lasted from about 2004 to 2008 but was soon followed and eventually outweighed by growing negative portrayals in the media (Melton et al., 2016). Early critiques of biofuels raised concerns that the net energy output from producing corn ethanol (net of the fossil energy used at each stage of the life-cycle of production) was negative and that ethanol was actually more carbon intensive than gasoline (Pimental and Patzek, 2005). This was followed by studies that raised concerns about the unintended consequences of biofuels for food and fuel markets and the leakage of carbon

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[1] Ethanol is a renewable biofuel made from a variety of biomass materials, including grains and crops with high starch and sugar content such as corn, sorghum, barley, sugar cane, and sugar beets. Ethanol can also be made from grasses, trees, and agricultural and forestry residues.

[2] For details, see Figure S1 in the on-line supplementary materials.

[3] The history of U.S. corn ethanol development, production, and policy support dates back to the 1970s. In recent years, its production grew as an oxygenate for gasoline that replaced Methyl Tertiary Butyl Ether (MTBE), which was phased out due to environmental concerns. Additionally, the Energy Policy Act of 2005, followed by the Energy Independence and Security Act of 2007, established the Renewable Fuel Standard and Renewable Fuel Standard II, respectively. The latter set ambitious volumetric targets for various types of biofuels and a total volume of 36 billion gallons of biofuels to be blended with fossil fuels by 2022. These policies have been supplemented with tax credits and import tariffs. See Lade et al. (2018) for a history of U.S. biofuel policy.

emissions due to land use change, known as indirect land use change (ILUC)-related carbon emissions.[4] This coincided with rising food prices in 2007-2008 and concerns about a growing share of corn being diverted to ethanol production, which led to fears that corn ethanol was leading to a food crisis and starvation among the poor (Runge and Senauer, 2007).[5]

Studies also questioned the oil displacement benefits of biofuels by noting that large scale displacement of gasoline in the US (a large importer of oil in 2007) could significantly lower world oil prices and cause a fuel "rebound effect". That is, as a result of the reduction in the world oil price of gasoline, fuel consumption could increase in the rest of the world, which means that a gallon of biofuel would displace less than an energy-equivalent gallon of gasoline globally, again making it more carbon-intensive than gasoline (Hill et al., 2016; Rajagopal, 2013; Rajagopal and Plevin, 2013)

These wide-ranging potential impacts of biofuels have led to a vast literature quantifying the impact of biofuels on food crop prices, land use change, and fuel prices. These studies have used a variety of techniques and produced a wide range of estimated impacts of biofuels on food crop prices, ILUC, and carbon emissions (see reviews in Khanna and Crago, 2012; Rajagopal, 2013; Zilberman et al., 2012).

Actual experience with biofuel production in the US has differed from both the early positive expectations and the later negative concerns that were raised. This article reviews the ex-ante projections, presents the empirical evidence that has emerged during the last two decades about the impact of increased U.S. biofuel production on food crop and fuel prices, land use

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[4] Indirect land use change occurs when the diversion of cropland for biofuels raises crop prices and returns to land and creates incentives for conversion of land with high carbon stock (e.g., forests, wetlands, peat land) to crop production, causing additional greenhouse gas emissions.

[5] https://d1tn3vj7xz9fdh.cloudfront.net/s3fs-public/file_attachments/bp114-inconvenient-truth-biofuels-0806_3.pdf

change, and GHG emissions, and discusses lessons learned and their implications for the future of biofuels.

The remainder of the article is organized as follows. The next section reviews the findings in the literature on the effects of biofuels on food prices. This is followed by a discussion of studies that examine the effects of biofuels on GHG emissions and land use. Then we describe the effects of biofuel policies on fuel markets and their implications for GHG emissions. This includes a discussion of the demand-side factors and consumer preferences that affect biofuel consumption. The penultimate section discusses other economic effects of biofuel policies. We conclude with a summary of the lessons learned from the U.S. experience with biofuels and their implications for the development of biofuels in the future and policies to support them.

EFFECTS OF BIOFUELS ON FOOD COMMODITY PRICES

There is a large literature that examines the relationship between food and biofuel prices since 2007. Oil prices increased by as much as 75% between 2005 and 2007, and during this time, legislation established targets and subsidies for U.S. biofuel use. The 2006-2008 period saw a very rapid expansion of biofuel production, due to rapidly rising energy prices and government subsidies. The resulting growth in demand for corn exceeded the supply capacity, leading to increased commodity prices in the short run. Energy prices declined as a result of the financial crisis of 2008, while crop supplies increased as a result of the high commodity prices of the previous periods. In this section, we review the literature on these relationships, focusing first on the conceptual frameworks that have been used to understand the links between food and fuel prices. Then we examine the empirical evidence of the relationship between food and fuel prices during the new millennium.

Basic Conceptual Framework

Rajagopal et al. (2007) introduced a simple conceptual framework for analyzing the impact of biofuels on food prices. As shown in Figure 1, the curve D_F is the initial demand and the curve S_0 is the initial supply of a food crop, such as corn, before the introduction of biofuels. The equilibrium quanitity is denoted by A and the equilibrium price is P_A. The introduction of biofuels leads to an increase in the demand for the food crop (shown by $D_F + B$), which causes the equilibrium quantity to rise to point B and the equilibrium price to rise to P_B. The crop price increases, because although the introduction of biofuels raises overall production of the food crop, it also diverts part of the food crop from consumers to biofuel production. This reduces the welfare of food consumers but improves the welfare of crop producers. Figure 1 also shows that the effect of biofuels on food prices may be partially offset if the higher prices lead to increased investment in agricultural supply or the introduction of new technologies, which cause supply to shift from $S_0$to S_1 and quantity to increase to C, which reduces the price to P_c. This suggests that the short-term positive effect of biofuels on food prices may be larger than the longer-term effect if the biofuel-induced increase in crop prices leads to more investment in research and growth in crop productivity.

In a subsequent study, de Gorter and Just (2008) developed a conceptual framework that links fuel and food prices and quantities to various policies and identifies plausible conditions under which biofuel prices would likely set a lower bound on food prices. Their pricing formula effectively related the "silent tsunami" of 2007-2008, when food prices tripled (de Gorter, Drabik, and Just, 2015), to the introduction of biofuel regulations in 2007. Tyner's (2010) analysis of the integration of the agricultural and energy markets suggested that the establishment of biofuel processing capacity created the potential for farmers to allocate their crops profitably to either food or energy markets, which means that energy prices set a floor on the price of corn. Mallory et al. (2012) found that the correlation between biofuel and food crop prices weakened later because ethanol use was constrained by the "blend wall" (an upper bound on the ethanol content of gasoline).

Ex-Ante Simulation Models

A number of studies have conducted ex-ante simulations of the impact of biofuels on food crop prices (Abbott, Hurt, & Tyner, 2008; Zilberman et al., 2012). While some of these studies used partial equilibrium models of food and fuel markets, others used general equilibrium models that considered the feedback between the food and fuel markets and the rest of the economy. Most of the studies were static, single period models, but several included a dynamic multi-period model and a few considered the effect of crop stocks on crop prices (see review in Khanna et al., 2014).

The features of these models affected the estimated impacts of biofuels on the prices of food, fuel, and other goods. One key concern is the assumptions about the responsiveness of crop yields and technological improvements to higher crop prices. A stronger response of technological change and crop yields to elevated crop prices leads to higher estimates of the supply-side response of the agricultural market to increased demand for biofuels. For example, the Global Trade Analysis Project (GTAP) model in Hertel et al. (2010) assumed the own price elasticity of corn yield to be 0.25. They found lower increases in agricultural acreage in response to the introduction of biofuel policies than the Food and Agricultural Policy Research Institute (FAPRI) model in Searchinger et al. (2008), which assumed this elasticity to be zero.[6] A positive yield price elasticity is consistent with the historical observation that periods of high farm prices

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[6] The GTAP and FAPRI models are general and partial equilibrium models, respectively.

are generally followed by investments in agricultural production that increase the supply of corn (Zilberman 2017). Miao et al. (2015) estimated a statistically significant own-price elasticity of corn yield of 0.23. This suggests that ex-ante simulations that assume the corn supply price elasticity to be zero would over-estimate the long term effect of biofuels on food crop prices, and recent evidence supports this conclusion. Indeed, today, more than 10 years after the 2007-2008 food price shock, agricultural commodity prices, especially corn, appear to be returning to historic lows, despite the large allocation of corn to the production of biofuels. These trends suggest that technological change enabled supply to catch up with the increase in demand for corn for food and biofuel.

The impacts of biofuels on crop prices vary depending on assumptions about the ease with which farmers are able to change crops or engage in double cropping (i.e., growing more than one crop on the land during a year), as well as assumptions about the productivity of marginal land that can be utilized if crop prices increase. More flexibility in cropping choice and higher productivity of marginal lands tend to reduce the impacts of biofuel on crop prices. Finally, models differed in the extent to which co-products of corn ethanol production, in particular Dried Distillers Grain Solubles (DDGS)[7], were used as livestock feed. In models that incorporated co-products, the diversion of corn to biofuel production had smaller impacts on crop prices and ILUC (Taheripour et al., 2018). More recent versions of the GTAP and FAPRI models (Taheripour et al., 2018; Carriquiry et al.,2019) that include the flexibility that farmers have to adapt to the introduction of biofuel policies produce much lower estimates of the impact of biofuels on crop prices and ILUC than the earlier versions in Searchinger et al. (2008) and Hertel et al. (2010).

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[7] DDGS are the remainder of corn kernels, after ethanol production is complete. They contain protein and are used for livestock feed, and displace the use of corn and soybeans as feed.

Several studies show that the spikes in crop prices in 2007-08 and 2010-11 occurred as a result of a combination of low crop inventories, growth in demand and changes in stock policies in China, high energy prices, stagnation of productivity growth due to under-investment in agricultural research, technology, and infrastructure, and restrictive trade policies. For example, Hochman et al. (2014) show that the rise in biofuel production in 2007-08 caused crop inventories to decline significantly, which affected corn prices. They estimate that biofuels accounted for about 20% of the increase in corn prices between 2001 and 2007 and another 10% of the price increase between 2008 and 2011. Other factors that contributed to the rise in commodity prices include growth in global incomes, exchange rate shocks, and energy shocks, which accounted for about 30%, 16%, and 11%, respectively, of the increase in corn prices between 2001 and 2007.

A meta-analysis of the impact of biofuels (Hochman and Zilberman 2018) suggests that biofuels have a greater effect on corn prices if the demand for corn is more inelastic and if policymakers rely on a mandate rather than a tax credit to bolster biofuel use.[8] Hochman and Zilberman (2018) also found that studies that used a general equilibrium framework (e.g., Golub et al. 2017), which incorporates linkages between agricultural and petroleum markets, resulted in lower estimates of the impact of biofuel policies than studies that used partial equilibrium models, which include a limited number of commodity markets (e.g., de Gorter, Drabik and Just 2015). The estimated impacts were lower in the general equilibrium models because the impacts of shocks are mitigated as they pass through multiple markets and reflect long-term adjustments (Hertel 2011). Finally, Hochman and Zilberman (2018) found that the impact of biofuels was stronger in agricultural commodity markets than in markets for final consumer products; in the

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[8] The meta-analysis was based on 59 estimates of the level and percentage change in corn prices relative to a baseline scenario (values from 2007),

long term, biofuels were estimated to increase corn prices by an average of 14%, while the impact on final consumer prices in the United States was estimated to be around 1%.

Econometric Studies

There have been relatively few econometric studies concerning the effect of biofuels on crop prices. Roberts and Schlenker (2013) found that biofuels increased the price of calories (they use calories to aggregate multiple commodities) in feedstocks by an estimated 20% if one-third of the corn used to produce ethanol is converted to co-products (e.g., DDGS) that are used as feed. In another empirical study, Carter et al. (2017) used a structural econometric model that incorporated storage effects to examine the impact of biofuel policies on food prices; they estimated that as a result of the increase in biofuel use, U.S. corn prices increased by 29% between 2006 and 2012. Hausman et al. (2012) estimated that the rapid reallocation of corn from feed to biofuel production during 2007-2008 was responsible for 27% of the increase in corn prices.

An alternative econometric approach for assessing the impact of biofuels on food crop prices is time series analysis, which does not rely on structural analysis of markets; rather it uses statistical tools to determine whether and to what extent the dynamics of fuel prices over time affect food prices and vice versa. More recent studies that have been able to use longer time series data provide a more comprehensive picture of the dynamics of prices.

To illustrate, Filip et al (2017) found that the relationship between fuel and food prices in three regions -- the United States, the European Union, and Brazil -- followed different patterns within three different time periods -- November 2003 to June 2008 (prior to the food price crisis), July 2008 to February 2011 (during the food price crisis), and March 2011 to May 2016 (after the food price crisis). Although biofuel prices were affected by food crop and fuel prices in all periods and in all three regions, biofuel prices had the greatest impact on food crop prices during the food crisis period. Filip et al. (2017) found that sugar prices in Brazil were affected by sugarcane ethanol prices before and during the crisis period, but that after the crisis, they were mostly affected by the interest rate. Thus, the Filip et al. (2017) time-series analysis suggests that the relationship between food and fuel prices varies over time and across regions and that the transmission of price effects is not smooth.

However, there is evidence that non-price factors also affected food crop and fuel prices in each of the three periods. Filip et al. (2017) found that in the pre-crisis period in Brazil, the variance in both sugar and ethanol prices was due mostly to external factors (e.g. the exchange rate, fuel prices), but during the food crisis period, a large share of the variance in ethanol prices (13%) was due to the variability in sugar prices, and this share increased to 30% after the crisis. However, they found that the variance in the price of ethanol had very little impact on the variance in sugar prices. Indeed, the variability in U.S. ethanol prices did not explain much of the variance in agricultural commodity prices before the crisis, but it explained about 15% of the variance during the crisis and about 10% of the variability after the crisis. Thus, the empirical analyses in Filip et al. (2017) suggest that biofuel prices had a limited impact on food prices, except during the crisis period, which supports the findings of Mitchel (2008), Wright (2014), and De Gorter, Drabik, and Just (2015), who find that biofuel policies were a trigger for the food crisis of 2008.

Although the different approaches used in the literature to assess the impact of biofuels on agricultural commodity prices, in particular corn prices, have produced diverse results, they do provide a consistent message. In particular, the literature suggests that the introduction of biofuel policies (e.g., the first Renewable Fuel Standard (RFS) in the US) between 2005 and

2007 was an important contributor to the high commodity prices between 2008 and 2011. The majority of the studies included in the Hochman and Zilberman (2018) meta-analysis and a few ex-post studies (e.g., Hausman, Auffhammer and Berck 2012) suggest that the effect of biofuels on agricultural commodity prices was between 10% and 30%, with the impact depending on the period of analysis, the approach, and other factors (e.g., income changes) considered.

EFFECTS OF BIOFUELS ON GREENHOUSE GAS EMISSIONS AND LAND USE

In this section, we review the literature quantifying the direct carbon intensity of biofuels as well as the ILUC-related carbon emissions.

Direct Life-Cycle Carbon Intensity of Biofuels

There is a large literature analyzing the direct life-cycle carbon intensity[9] of biofuels relative to the fossil fuel they are intended to replace (Farrell et al., 2006; Khanna and Crago, 2012). Initial concerns raised by Pimentel and Patzek (2005) that the energy input and the direct lifecycle carbon intensity of corn ethanol were larger than those of gasoline were found to result from flawed assumptions and methods, including accounting for labor energy input (rather than fossil energy only) and ignoring the energy output embodied in the coproducts (i.e., DDGS) that accompany corn ethanol production (Farrell et al., 2006).

Indeed, a rigorous assessment by Farrell et al. (2006) concluded that corn ethanol's energy output to input ratio was 1.2 and that its direct life-cycle carbon intensity was 18% lower than that for gasoline, implying that corn ethanol production leads to an increase in net energy produced and lower carbon intensity compared to fossil fuels (on an energy-equivalent basis).

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[9] The direct life-cycle carbon emissions of ethanol is the sum of all carbon emissions generated during the various stages in the process of producing ethanol, from the farm to the gas station (or beyond, including the delivery to the vehicle), net of the carbon credit for co-products produced that displace fossil fuels. Emissions intensity of ethanol is defined as life-cycle carbon emissions per unit of energy (mega-joule) to make it comparable to the emissions intensity of energy-equivalent gasoline.

The energy output to input ratio has been increasing while the carbon intensity of corn ethanol has been declining over time, due largely to the reduction in energy use in ethanol plants and a switch from coal to natural gas as the energy source (Wang et al., 2011). The energy content of corn as a feedstock has also declined due to significant reductions in both the fertilizer intensity of corn and energy use in corn farming. Moreover, the type of fuel used as an input for ethanol production (coal, natural gas, or biomass) and whether the ethanol co-products were dried or consumed wet by livestock can cause the direct life-cycle carbon intensity of corn ethanol to range from being slightly higher than gasoline (if it is produced using coal energy) to being almost 40% lower than gasoline if natural gas is used and co-products are wet (Wang et al, 2007).[10]

Some recent studies have questioned the assumption that corn used for ethanol is inherently biogenically carbon neutral (see review in Khanna et al. 2020).[11] According to these studies, corn used for ethanol would be carbon neutral only if all of this corn were obtained from additional production (i.e., not by diverting it from corn that would otherwise have been produced for food and feed). Khanna et al. (2020) present an approach for estimating these biogenic emissions and show that even if they are included with the direct life-cycle carbon emissions intensity of corn ethanol, the overall carbon intensity of corn ethanol (not including ILUC-related emissions) is 21% lower than gasoline.

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[10] For example, data on ethanol produced in California indicate that there are a number of options for producing corn ethanol, with GHG intensities that range from about 50 gCO2/MJ (grams of carbon-dioxide per mega-joule) to about 85 gCO2/MJ[10] (see Figure S2 in the on-line supplementary materials). This suggests that corn ethanol could achieve a reduction in direct life-cycle carbon intensity that ranges from 10% to 41% relative to gasoline (which has a carbon intensity of 94 gCO2/MJ).

[11] Biogenic carbon is the carbon taken up by the corn plant during photosynthesis, which becomes embodied in the plant. When corn is converted to biofuel and combusted in the vehicle, this carbon is released back into the atmosphere. Since this carbon is considered to be part of the natural carbon cycle (i.e., recycled carbon), corn used for ethanol is assumed to be biogenically carbon neutral and biogenic emissions are typically not included in the direct life-cycle emissions of corn ethanol.

ILUC-Related Carbon Intensity of Biofuels

Searchinger et al. (2008) shifted attention from the direct life-cycle carbon intensity of corn ethanol to the ILUC-related carbon intensity of biofuels, which results from an increase in crop prices and land rents caused by the diversion of corn from food to fuel. Increased demand for land by one crop affects land allocation for all competing crops, thus affecting their production and prices and increasing overall land rents. Moreover, for global crop markets, of which the US has a large market share, changes in the supply of major crops produced in the US will affect world market prices for agricultural commodities and potentially lead to ILUC globally. In the remainder of this discussion of ILUC, we discuss the estimates of the ILUC effect in the literature and the determinants of these estimates.

Estimates of the ILUC effect

A large literature has emerged over the last decade that quantifies the ILUC effect of biofuels. This literature uses global general equilibrium and partial equilibrium models to simulate the effect of an exogenous shock to biofuel production (from some baseline level) on equilibrium agricultural commodity prices, land use, and carbon stored in soils, vegetation, and forests. These effects are then compared to a baseline or counterfactual land use (i.e., in the absence of biofuels). These studies have produced a wide range of estimates, which depend on the type of model and its parametric assumptions (see review in Khanna and Crago, 2012).[12]

In the first study to quantify the ILUC effect, Searchinger et al. (2008) use a partial equilibrium model[13] and find that producing 15 billion gallons of corn ethanol would lead to an estimated 10.78 million hectares of land (or 0.73 hectares (ha) per 1000 gallons) being converted to crop production globally. They estimate that this would result in an ILUC-related

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[12] See Figure S3 in the on-line supplementary materials for a comparison of these estimates.

[13] They use the Center for Agricultural and Rural Development (CARD)/FAPRI global agricultural outlook model.

GHG emissions intensity for corn ethanol of 104 g CO_2/MJ and would make ethanol more carbon-intensive than gasoline (which typically has a carbon intensity of 94 g CO_2/MJ), without even including its direct life-cycle carbon emissions intensity. In contrast, using the general equilibrium GTAP model, Hertel et al. (2010) produce a substantially lower estimate -- 0.33 ha per 1000 gallons (1 gallon =3.785 liters) -- and an associated ILUC-related emissions intensity of 27 g CO2/MJ. More recent estimates of the ILUC effect of biofuels have tended to be lower, as models have improved and assumptions have become more realistic and consistent with observed data.[14] The most recent estimate of the ILUC-related emissions intensity using the GTAP model is 13.3 gCO2/MJ, without allowing for intensification of cropland (e.g., through double cropping), and 8.7 gCO2/MJ, with intensification of cropland (Taheripour et al, 2017, 2018). Similarly, using an improved FAPRI model, Carriquiry et al. (2019) estimate these emissions to have a lower bound of 9.7 gCO2/MJ.

Determinants of the ILUC effect

Key assumptions that have been shown to affect these estimates of the impact of biofuels on ILUC are the availability and productivity of marginal cropland, the responsiveness of crop yields to higher prices, and the potential for double-cropping of land (Taheripour et al. 2017; Khanna and Crago, 2012). For example, the ILUC- related GHG intensity estimates in Searchinger et al. (2008) fall significantly when crop yields are price elastic and when overly restrictive assumptions about the ability to convert idle cropland to crop production in the US are relaxed (DuMortier et al. 2012). The lower estimates obtained using the GTAP model[15] are due at least in part to the assumption of a positive elasticity of corn yield with respect to price of 0.25 (Hertel et al 2010), which is similar to the empirical estimate in Miao et al. (2015). Recent

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[14] See Figure S3 in the on-line supplementary materials.

[15] See Figure S3 in the on-line supplementary materials.

versions of the GTAP model introduced the potential to intensify cropland use through multiple-cropping of the land at varying rates across different regions in the world (Taheripour et al. 2017, 2018). These models also assumed larger values for yield elasticities with respect to price (0.3 in the US and 0.325 in Brazil, rather than 0.25 in both countries). These modifications have reduced the land requirements for ethanol by more than half (compared to previous versions of the model) and the land use change related emissions intensity to 8.7 gCO2/MJ (Taheripour et al., 2018).[16] Similarly, Carriquiry et al., (2019) find that the ILUC-related emissions intensity of corn ethanol in the US (estimated using the FAPRI model) is reduced when double cropping and endogenous crop-yield price relationships are included.

Early versions of the GTAP model also made a number of other restrictive assumptions, including that marginal land is 66% as productive as existing cropland and that the ease of transformation of land across different land uses (forest, pasture, and cropland) and alternative crops is globally homogeneous (see Khanna et al., 2014). Subsequent versions of the GTAP model show that when heterogeneity is introduced into the land transformation elasticity across agro-ecological zones, the ILUC-related emissions from corn ethanol are reduced by 12% compared to a model with uniform land transformation elasticity (see Khanna and Crago, 2012), suggesting that more realistic assumptions led to lower estimates. Further modifications to the GTAP model, including considering cropland pasture as available marginal land in the US and Brazil, improved parameters representing the productivity of this land relative to existing cropland, and more realistic land transformation elasticities that varied across regions based on

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[16] Also see Figure S3 in the on-line supplementary materials.

real-world observations of land use changes around the world, also lowered estimates of the ILUC effect (Taheripour et al., 2018, 2019).[17]

Recent studies have also shown that a one-time shock to biofuel production leads to a much higher estimate of the ILUC effect in a static model than in a dynamic model, in which biofuel production rises gradually over time (Golub et al., 2017; Chen and Khanna, 2018). For example, using a dynamic version of the GTAP model that incorporates changes in technology, Golub et al. (2017) show that the global cropland change due to biofuels falls from 0.15 ha per 1000 gallons to 0.02 ha per 1000 gallons in 2030. Similarly, Chen and Khanna (2018) apply a dynamic optimization model to show that the conversion of land from non-crop to crop production increases at a lower rate than the increase in production of corn ethanol; as a result, the ILUC due to biofuels production declined from 0.14 ha per 1000 gallons in 2007 to 0.05 ha per 1000 gallons in 2012. This is, in part, because once land is converted from non-crop to crop production it can be used repeatedly for biofuel production in the future and also because increased crop yields over time result in a lower ratio of cumulative land conversion to cumulative biofuel production over time. Indeed, Chen and Khanna (2018) find that the doubling of U.S. corn ethanol production between 2007 and 2012 led to only a 1% increase in total cropland through the conversion of cropland pasture and land enrolled in the Conservation Reserve Program (CRP).[18]

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[17] When multiple cropping, higher yield elasticity with respect to price, greater ease of conversion of grassland to crop production, and intensification of pasture use for livestock production are allowed, the estimated land use change and related emissions-intensity of other biofuels, such as sugarcane ethanol, have also been found to decline -- from high initial estimates of 46 gCO2/MJ (CARB, 2009) to about 14 gCO2/ MJ (Harfuch et al. 2017) and 4.7 gCO2/MJ (Taheripour et al. 2018). Similarly, Souza et al. (2017) show that the ILUC effect of sugarcane ethanol production in Brazil decreases substantially after incorporating the fact that most sugarcane expansion is in southeastern Brazil, which has high productivity; additionally, the availability of low productivity pasture in Brazil, implies that the impact of sugarcane ethanol on food security and beef prices is very small (Arima et al, 2017).

[18] The CRP is a land retirement program that offers 10-15 year contracts to farmers for retiring cropland in environmentally sensitive areas. When a contract expires, farmers have the option to convert the land back to crop production.

Empirical evidence of land use change due to biofuels

While there is a large literature that simulates the ILUC effect of biofuels, empirical evidence of this effect (i.e., using observed data) has been very limited thus far. Data from the U.S. Department of Agriculture indicates that aggregate cropland in the US stayed relatively constant between 2000 and 2014, although there was a shift among crops (Dunn et al. 2017).[19] A number of studies have used satellite data to compare cropland trends between 2008 and 2012 and find that there has been a substantial expansion of cropland in the United States over this period, particularly in regions close to an ethanol refinery (Wright et al., 2017; Lark et al., 2015). These studies implicitly attribute the entire change in land use to corn ethanol and do not explicitly quantify the causal effect of the expansion of corn ethanol on land use change. In an analysis of the causal effect of crop price changes and increased ethanol capacity on cropland in the US over the 2008-2014 period, Li et al (2018) find that, ceteris paribus, the increase in ethanol capacity led to only a 1% increase in total crop acreage between 2008 and 2012 and that the increase in corn prices led to a 2% increase in total crop acreage. However, the effect of crop prices on total crop acreage was largely reversed by 2014 due to the downturn in crop prices after 2012; as a result, total crop acreage in 2014 was only 0.5% higher than in 2008. This study indicates that crop prices have a fairly small effect on land-use change and that the effect is transitory and can be reversed as crop prices change over time.

Overall, this literature suggests that the high initial estimates of the effect of biofuels on ILUC were driven largely by stringent model assumptions and have not been supported by either recent models (that have more advanced features) or the empirical evidence that has emerged over time. Khanna et al. (2017) analyze the consequences of including these high estimates of

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[19] See Figure S4 in the on-line supplementary materials for details.

the ILUC-related carbon intensity of biofuels in the overall carbon intensity of the different types of biofuels that are used to determine their compliance with a Low Carbon Fuel Standard (LCFS). They find that this approach would lead to only a small (1-3%) additional reduction in carbon emissions but at a welfare cost that would be 20% to 360% greater than the social cost of carbon.

IMPACTS OF BIOFUEL POLICIES ON FUEL MARKETS AND IMPLICATIONS FOR GREENHOUSE GAS EMISSIONS

Reduction in fossil fuel consumption is one of the major objectives of biofuel policies. However, the extent to which these policies actually reduce dependence on fossil fuels will depend on both the effect of biofuels on consumer fuel prices and the policy used to incentivize the blending of biofuels with fossil fuels. A mandate such as the RFS imposes an implicit tax on domestic gasoline consumption and an implicit subsidy on the biofuel. At the same time, by reducing demand for imported oil, it can affect the world market price of oil and thus gasoline. This means that the net effect of biofuels on the price of the domestic ethanol-blended fuel can be positive or negative, and thus the mandate may increase or decrease domestic fuel consumption. A reduction in the world market price of oil can be expected to increase the consumption of oil in the rest of the world (Chen et al., 2014; Rajagopal et al 2015). This rebound in oil consumption may offset the GHG savings achieved by the substitution of gasoline with biofuels domestically. In the remainder of this section, we provide an overview of the literature on the impacts of biofuel policies on fuel markets and the demand for biofuels.

Impact of Biofuel Policies on the Price of Blended Fuel and GHG emissions

A number of studies have simulated the impact of biofuel mandates on the price of blended fuel in the United States as well as the world price of oil (Chen and Khanna, 2012; Rajagopal, 2013; Bento et al., 2015); the impacts were generally found to be small and have varied over time and across regions (GAO, 2019). These studies estimate that gasoline prices declined by \$0.04-\$0.10 per gallon and that the magnitude depends on the volume of biofuel blended and the assumed elasticities of supply and demand in different regions. Studies that also model upstream oil markets estimate a smaller effect than studies that focus only on finished fuel markets. Based on a meta-analytic comparison of existing studies, Hochman and Zilberman (2018) find that ethanol production reduced the price of the blended gasoline by 4.5%. Although almost all studies that simulate the impact of biofuel policies on the price of blended fuel assume a competitive global crude oil market in which the price of oil is based on its marginal cost, Hochman et al. (2011) examine the implications of strategic behavior by a cartel of oil producing nations. In this model, in order to mitigate the negative impact of increased biofuel production on oil prices, the cartel responds by lowering oil production. Thus, Hochman et al. (2011) argue that models of perfect competition overestimate the reduction in the world oil price and thereby overestimate the rebound in oil consumption and emissions.

The magnitude of the rebound in fuel consumption (due to the biofuel-induced reduction in the blended fuel price) depends on various factors, including assumptions about the elasticity of demand for vehicle miles travelled (or the elasticity of demand for gasoline) in the US and the elasticity of oil demand and supply in the rest of the world. Several studies in the broader economics literature find that the price elasticity of demand for gasoline in the US is very low and has been declining over time (due to a reduction in the share of income spent on fuel), ranging from 0.034 to -0.077 between 2001 and 2006 and from -0.21 to -0.34 between 1975 and 1980 (Hughes et al., 2008; Greene, 2012). This suggests that the magnitude of the domestic rebound effect is likely to be low. There is also considerable uncertainty about the elasticity of oil supply in the rest of the world and OPEC’s capacity for a strategic response to an expansion in biofuel production, which could affect the responsiveness of oil supply and price. With respect to GHG emissions, these studies again suggest fairly small overall effects of corn ethanol, depending on assumptions about the elasticity of petroleum supply and demand for vehicle miles travelled (Thompson et al., 2011; Bento et al., 2015; Rajagopal et al. 2015; GAO, 2019; Hochman and Zilberman, 2018).

Unlike first generation biofuels from food crops like corn, second generation biofuels are those produced from crop residues (e.g., corn stalks and husks, sugarcane bagasse) and high yielding dedicated energy crops (e.g., switch grass, miscanthus) that could be grown on lower quality land and thus also mitigate competition with food crop production. Such biofuels hold greater potential for reducing carbon emissions and have much lower ILUC effects (Dwivedi et al., 2015). Hudiburg et al. (2016) estimate that 32 billion gallons of biofuels that include 16 billion gallons of cellulosic biofuel (from biomass feedstocks) and 15 billion gallons of corn ethanol could reduce direct GHG emissions in the US by 7% (relative to a no-policy scenario) and by 4% (when ILUC and fuel rebound effects are included). The estimates would be much higher (12% and 9%, respectively) if the 15 billion gallons of corn ethanol were displaced by an equivalent amount of cellulosic biofuels. This suggests that biofuels, particularly second generation biofuels, have considerable potential to reduce GHG emissions from the transportation sector.

Effects of Demand-Side Rigidities and Heterogeneous Consumer Preferences

We next discuss a strand of the literature that focuses on demand-side rigidities, such as constraints on ethanol blending due the distribution infrastructure and vehicle stock, and the implications of heterogeneity in consumer preferences for biofuels.

Conventional gasoline vehicles are currently designed to accept pre-blended gasoline with up to 15% ethanol by volume (E15). When adopted in 2007, the RFS target of 36 billion gallons of ethanol consumption in 2022 amounted to 26% of annual U.S. consumption of finished motor gasoline in 2007.[20] The U.S. Energy Information Administration's 2007 Annual Energy Outlook forecast cumulative growth of 4% in U.S liquid fuel consumption between 2007 and 2022.[21] However, both the existing stock and the projected growth of vehicles that could accept blends with more than 10% ethanol (henceforth called flex-fuel vehicles) and the required retail biofuel distribution infrastructure were well below what would be needed to achieve the RFS targets. With this in mind, the Energy Security and Independence Act of 2007 emphasized the need to establish programs to develop infrastructure for storing and dispensing renewable fuel blends.[22]

However, increased consumption of higher percentage ethanol blends requires incentives both for the adoption of flex-fuel vehicles (which have higher upfront costs) and to fuel them with higher blends when consumers face choices at the pump. In the US, the two major retail blends are E10 (10% ethanol by volume) and E85 (85% ethanol by volume). Because ethanol has lower volumetric energy density relative to gasoline, E85 has lower energy content than E10. Thus, to encourage owners of flex-fuel vehicles to buy E85, it would need to be priced lower than E10. Compliance with the RFS requires regulated parties (i.e., the blenders) to hold a certain number (in proportion to their fuel sales) of tradable permits called Renewable Identification Numbers (RINs), with each gallon of biofuel produced or imported generating a RIN, which is acquired by the buyer of that unit of biofuel. In a competitive equilibrium, the

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[20] https://www.eia.gov/tools/glossary/index.php?id=Motor%20gasoline%20(finished)

[21] https://www.eia.gov/outlooks/archive/aeo07/gas.html, https://www.eia.gov/outlooks/archive/aeo07/excel/figure82_data.xls

[22] https://www.congress.gov/bill/110th-congress/house-bill/6

value of the RIN is the difference between the marginal costs of fossil fuel and biofuel, which is the marginal cost of compliance with the RFS. RINs thus function as a tax on the fossil fuel producer and a subsidy to the biofuel consumer.

Theory suggests that when the blend limit becomes binding (i.e., consumption of E10 blends is at its upper limit), due to the progressively lower energy content of higher percentage ethanol blends, a higher RIN subsidy should be passed through to consumers in the form of a discounted retail price for higher blends (e.g., E85) relative to lower blends (e.g., E10). Empirical studies find that this pass through is not always complete. For instance, there was a complete pass-through of RIN prices into wholesale prices in the E10 market, but the pass-through has been zero to 75% in the E85 market (Knittel et al.l 2017; Li and Stock; 2018; Lade and Bushnell, 2019). However, the underlying reasons for this incomplete pass-through and the appropriate policy remedies are as yet unclear. Plausible explanations include imperfect retail competition in the E85 market and the option for blenders to comply with the RFS by selling more advanced biofuel (i.e., biodiesel), which did not face blending constraints, rather than pricing E85 low enough to induce consumption of higher blends of ethanol (Korting and Just, 2017). This imperfect pass-through has reduced incentives for expanding fuel infrastructure for higher ethanol blends and, in turn, sales of flex-fuel vehicles (Du and Li, 2015); indeed, as of 2017, less than 10% of vehicles in the US were flex-fuel vehicles.[23] Moreover, the US Environmental Protection Agency's repeated issuance of waivers (to fuel blenders) from ethanol blending obligations, irrespective of the economic merits, reduces incentives for investments that would ease the blend wall and increase demand for higher blends of ethanol.[24]

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[23] https://afdc.energy.gov/data/10355

[24] https://www.dtnpf.com/agriculture/web/ag/news/business-inputs/article/2020/08/06/rfas-cooper-epa-decision-issue-blend

Most of the studies discussed here assume that the willingness to pay for biofuels depends on their functional benefits -- i.e., as a fuel for transportation. However, a few studies on the US and Brazil suggest that consumer preferences for biofuels are heterogeneous and that a substantial percentage of households is willing to pay a premium for biofuels, presumably because of their perceived positive environmental and social attributes, while a different subset of households is unwilling to purchase biofuels unless its price is at par or below its energy value (Anderson, 2012; Salvo and Huse, 2013).

OTHER ECONOMIC EFFECTS OF BIOFUEL POLICIES

U.S. biofuel policies have other economic effects that are often overlooked in traditional welfare analysis, including impacts on technical change and the balance of trade. The US corn ethanol industry has been evolving for more than four decades. For much of that time, the industry has been viewed as an infant industry needing government support in the form of tax credits (which have imposed costs on taxpayers), protection from imports, and mandates to increase consumption. These policies have been effective in inducing significant technical change in the industry. Chen and Khanna (2012) find that the processing costs of US corn ethanol declined by 45% between 1983 and 2010, while production volumes increased seventeen-fold; learning by doing and economies of scale played an important role in reducing these processing costs. Similarly, the cost of producing sugarcane ethanol in Brazil declined by 70% between 1975-2010; however, Chen et al. (2015) show that this decline was due largely to exogenous technological change. As a result of reduced production costs, corn ethanol and sugarcane ethanol have become competitive with oil production in both countries and are no longer supported by tax credits. Indeed, these biofuels are now meeting 10% of fuel demand in the US and close to 30% of fuel demand in Brazil.

In the United States, corn ethanol has also contributed to an improvement in the US trade balance. Hochman and Zilberman (2018) estimate that ethanol production reduced the U.S. trade deficit by about $50 billion (or 8.2%) in 2011. Additionally, biofuels helped to improve the terms-of-trade for the US, by raising the price of U.S. agricultural commodity exports and lowering the demand for and price of imported crude oil. Cui et al. (2011) show that this improvement in the terms-of-trade is the main reason biofuel mandates (RFS and others) have had a net positive welfare impact in the US, even without considering the energy security benefits of reducing dependence on foreign oil. However, studies have also found that the biofuel tax credit imposed net welfare costs on the US economy even when the reduced need for subsidies to corn producers (due to higher crop prices induced by biofuels) is taken into account (Du et al., 2009).

CONCLUSIONS

Concerns about the unintended effects of biofuels on commodity markets, land use, and GHG emissions have led to skepticism among policy makers, researchers, and the public about the merits of expanding biofuel production. This article has reviewed U.S. experience with biofuels over the last two decades and its economic and environmental implications. The findings of our review provide several lessons that can help inform the debate about biofuels and future policies to support them. First, it appears that the concerns raised about the impacts of biofuels on food and ILUC are more relevant in the short run than in the long run. Indeed, the adverse impact of biofuels on agricultural commodity prices in the short run was exacerbated by other factors, including low crop stocks, high energy prices, and growing demand for food. Over time, agricultural supply responded to higher prices by raising productivity and changing cropping patterns, suggesting that market demand can induce technological change that increases the capacity of the agricultural sector to meet growing demands for both food and fuel in the long run. Thus, in the long run, the demand and supply of agricultural commodities tends to be more elastic, which can mitigate the food vs fuel effects (Hertel, 2011).

Second, the empirical evidence indicates that crop acreage is fairly inelastic even with the high crop prices caused by biofuels over the last decade. This suggests that the ILUC effect of biofuels is likely to be small, at least in the aggregate, although the magnitude of this effect may vary spatially. Third, policies aimed at increasing the production of corn ethanol have taken four to five decades to result in a mature industry. Thus, expectations that the RFS established in 2007 could induce production of a billion gallons of cellulosic biofuels in five years were not realistic. In fact, the evidence indicates that in many cases, technology-forcing policies need to be maintained over a long time period to encourage the development of new technologies. Moreover, significant investment in research and development and capital is required to establish a new industry. Fourth, existing studies indicate that second generation biofuels from cellulosic biomass feedstocks have significant potential to reduce GHG emissions with even more limited adverse impacts on food crop prices and ILUC than corn ethanol. Finally, the limited success of supply-side biofuel policies (e.g., RFS) over the last decade indicates the need to design policies that stimulate a demand for biofuels that matches the growth in potential supply. In particular, stimulating demand for higher percentage ethanol blends requires addressing inefficiencies in the pass-through of the RIN subsidy to the retail market, targeting incentives for the purchase of higher percentage blends that are based on heterogeneous preferences for ethanol, and encouraging investments in retail distribution infrastructure for higher percentage blends.

Despite recent developments in electric vehicles, it is essential to continue to develop low carbon biofuels to reduce the GHG emissions from the transportation sector. Even with aggressive policies aimed at increasing demand for electric vehicles, liquid fuels are expected to continue to be needed to meet growing transportation demands around the world (Debnath et al., 2019). In some sectors, such as the aviation, long-distance trucking, and marine sectors, where batteries face technical and economic barriers, low carbon biofuels provide a viable option for reducing the carbon footprint. Thus, a critical step is to reduce both supply and demand side constraints to bioenergy by shifting emphasis away from food crop-based feedstocks to next generation feedstocks (e.g., dedicated perennial energy crops) and to biofuels that are perfect substitutes for their fossil equivalents, such as renewable diesel and bio-jet fuel. Over the longer term, policy certainty will also be essential for promoting the development and implementation of an infrastructure to enable both the demand and supply of higher percentage blends of biofuels.

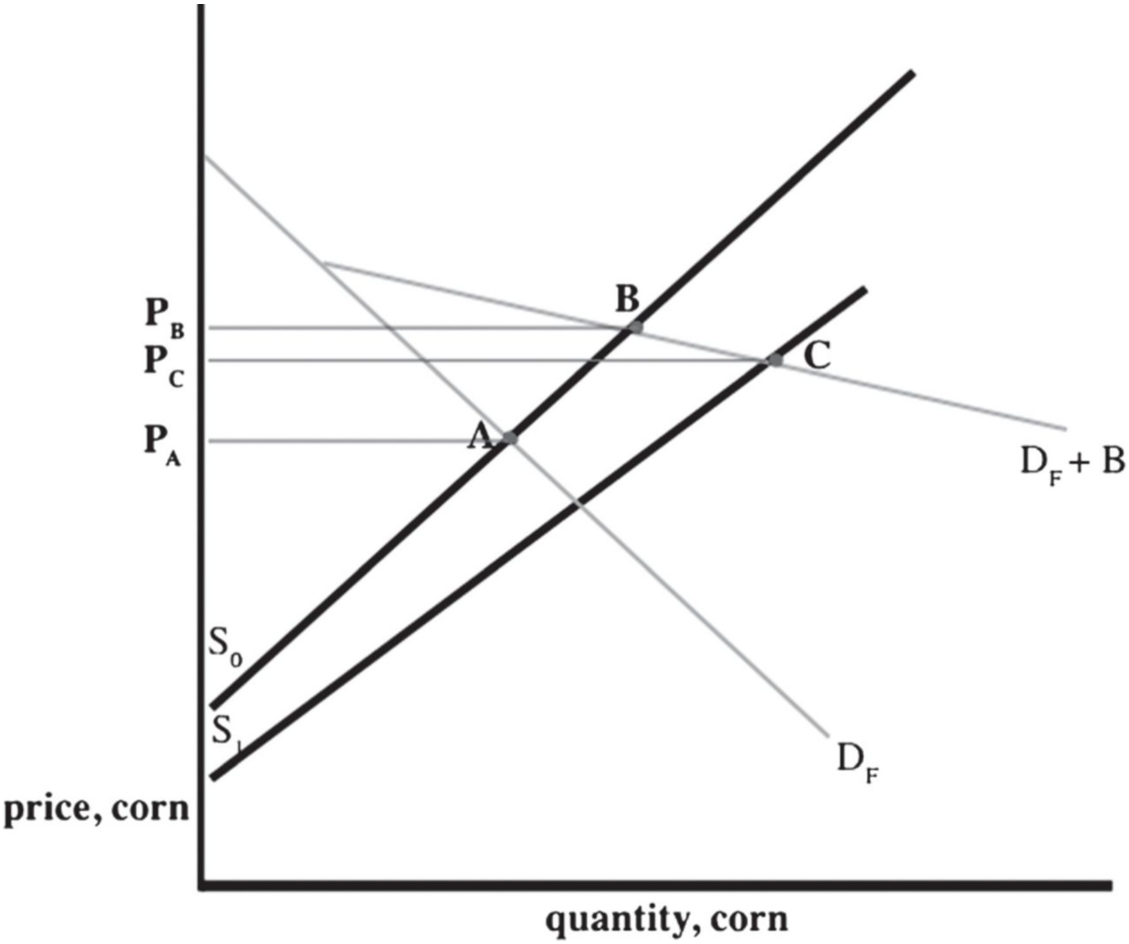

Figure 1: Effect of Demand for Ethanol on Corn Price
Source: Adapted from Rajagopal et al. (2007)

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