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Impacts of Ethanol Policy on Corn Prices: A Review and Meta-Analysis of Recent Evidence

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Impacts of Ethanol Policy on Corn Prices: A Review and Meta-Analysis of Recent Evidence

Nicole Condon, Heather Klemick, and Ann Wolverton[1]

Abstract

The literature on the impacts of biofuels on food prices is characterized by contradictory findings and a wide range of estimates. To bring more clarity to this issue, we review studies on U.S. corn ethanol expansion released between 2008 and 2013. Normalizing corn price impacts by the increase in corn ethanol volume, we find that each billion gallon expansion in ethanol production yields a 2-3 percent increase in corn prices on average across studies. We also conduct a meta-analysis to identify the factors that drive the remaining variation in crop price impacts across studies. We find that the modeling framework, projection year, inclusion of ethanol co-products, international biofuel production, and baseline and policy ethanol volumes explain much of the differences in price effects across studies and scenarios. Our study also distinguishes between analyses that estimate long-run equilibrium impacts of biofuels and short-run studies that consider the effects of unexpected policy or weather shocks, which can lead to temporary price spikes. We find higher impacts on corn prices per billion gallons of corn ethanol production in studies using a short-run framework; each additional billion gallons of ethanol causes a 5-10 percent increase in corn prices. Last, we examine a small number of studies that consider the implications of biofuel policies for food security worldwide. The literature suggests that biofuels expansion will raise the number of people at risk of hunger or in poverty in developing countries.

Key words: ethanol, biofuels, Renewable Fuel Standard, food prices, food security, meta-analysis

Subject area: Agriculture: Land Use, Energy, Environmental Policy, Transportation

JEL classification: C54, Q16, Q18, Q42

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1. Introduction

During the last decade, there has been more than a five-fold increase in global biofuel production. The U.S., Brazil, and the European Union lead the world in biofuel production, bolstering their biofuel industries with mandates, subsidies, and favorable trade policies. The International Energy Agency (2011) has projected that the share of biofuels in global transportation fuel will increase from the current 2 percent to 27 percent by 2050.

The growth in biofuel production has been mirrored by a rise in food prices. After nearly 30 years of low or decreasing prices, world commodity prices began rising in the mid-2000s, with the FAO food price index reaching a historical high in the summer of 2008 that was surpassed in late 2010 (FAO, 2013). The confluence of these two trends has triggered a debate surrounding the tradeoff between food and fuel resources. U.S. biofuel policies have received particular scrutiny because of the U.S.'s role as a leading exporter of agricultural commodities.[2] However, correlation alone is not sufficient to establish a causal link between biofuel production and crop prices.

This policy issue has spurred an extensive literature by academics, government agencies, and other organizations examining the economic, social, and environmental impacts of biofuels. Effects of biofuels on agricultural commodity and retail food prices have received considerable attention. This literature is characterized by contradictory findings and a wide range of estimated impacts. Recent reviews of the literature highlight this range: Zhang et al. (2009a) find projections ranging from 5 to 45 percent for increases in the price of corn by 2015 as a result of biofuel policy, while literature summarized by the National Research Council (2011) on the proportion of the 2007-2009 food price spike attributable to biofuels includes estimates from 17 to 70 percent. Such divergent results make it difficult to assess the relative merits of policies that reduce, expand, or otherwise alter biofuel production trends.

To bring more clarity to the issue of biofuel impacts on food prices, we review the recent literature on U.S. corn ethanol expansion. Restricting the scope of our study to a single feedstock—corn—and to studies released between 2008 and 2013, we control for differences across studies in modeling technique, feedstocks, time period, scenario, technology, and other assumptions. Zhang et al. and the National Research Council note that the differences across studies make it nearly impossible to compare results or estimate impacts with any accuracy. However, we employ several strategies in an attempt to place studies on a similar footing. First, to control for the large differences in ethanol volumes considered across different scenarios, we normalize corn price impacts by ethanol quantity to

[2] In the 2011-2012 marketing year, U.S. production accounted for approximately 33 percent of world corn exports, 18 percent of wheat exports, and 40 percent of soybean exports (USDA 2013a).

calculate two metrics: the percent change in corn prices per one billion gallon increase in corn ethanol production (a semi-elasticity measure), and the percent change in corn prices per one percent increase in corn ethanol production (an elasticity measure). Looking across studies and scenarios, we find that each billion-gallon expansion in corn ethanol production (or alternately, each 10 percent expansion in production) yields a 2 to 3 percent increase in long-run corn prices on average.

While these normalized price metrics make for more straightforward comparisons across studies, considerable differences still remain. Therefore, we also conduct a meta-analysis to parse the contribution of key assumptions and structural choices to estimates. The meta-analysis allows us to identify which factors drive the large differences in commodity price impacts across studies. We estimate the meta-analysis using a random effects model to address the fact that estimates from the same study are not independent. We find that the modeling framework (partial versus general equilibrium), projection year, inclusion of ethanol co-products, international biofuel production, use of corn as the examined commodity, and baseline and policy ethanol volumes explain much of the variation in price effects across studies and scenarios.

Our study also distinguishes between analyses that estimate long-run equilibrium impacts of biofuels and short-run studies that consider impacts before markets have time to fully adjust to policy changes. Most of the literature to date has only examined long-run impacts, typically several years into the future, but a few recent studies have considered the effects of unexpected policy or weather shocks over a limited time horizon, which can lead to temporary price spikes. Unsurprisingly, we find much higher impacts on corn prices per billion gallons of corn ethanol production in studies using a short-run framework—each additional billion gallons of ethanol is associated with a 5 to 10 percent increase in corn prices on average. Such short-term disruptions to commodity prices could have important implications for food security among low-income people without consumption-smoothing options even if the long-run impacts of biofuels are modest.

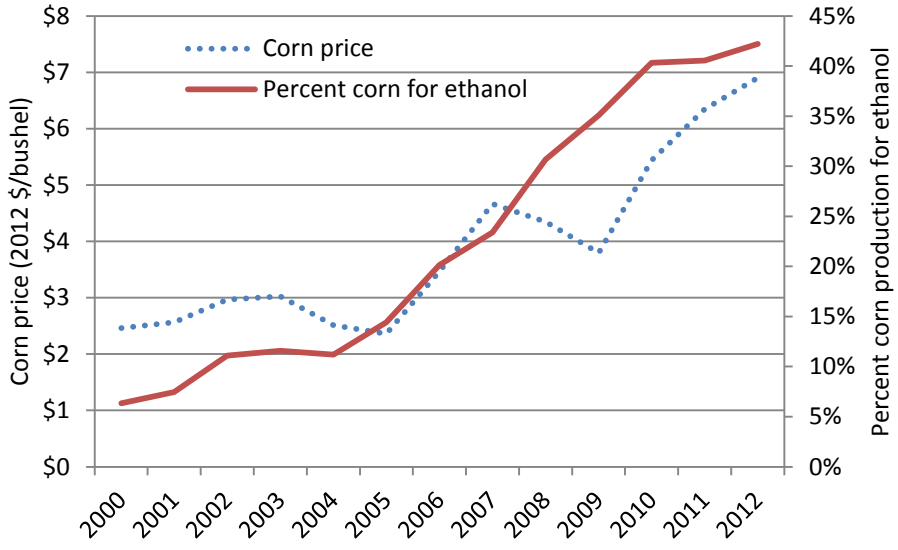
We also examine a small number of studies that explicitly consider the impacts of biofuel policies on food security worldwide. Raw commodities make up a small proportion of the cost of finished food products in high-income countries, muting the effects of commodity price rises, but they may be felt more acutely in low-income countries where raw commodities make up a large share of household budgets. While the literature is characterized by heterogeneous findings, it suggests that biofuels expansion is likely to raise the numbers of people at risk of hunger and/or in poverty in developing countries on balance.

The paper is structured as follows. The background section discusses trends in U.S. biofuel policy and corn prices. Next is our review of long-run studies of the impact of U.S. corn ethanol production on corn prices. We identify 18 studies released since 2008 that provide sufficient information to include in our review. Because many studies examine several scenarios, we include a total of 78 estimates in the meta-analysis. The following section of the paper turns to short-run studies. We normalize the corn price results to allow for comparisons with the long-run studies, but we do not perform a meta-analysis in this section because only five short-run studies were identified. The next section discusses the link between biofuels-driven commodity price increases and food security. A final section concludes by summarizing the findings and identifying areas for further research.

2. Background: Historic U.S. Policy and Price Trends

Ethanol is the primary biofuel produced in the United States, with corn-based ethanol comprising more than 90 percent of domestic ethanol production (U.S. DOE 2011). From 2000 to 2012, U.S. ethanol production increased by more than 700 percent, from 1.6 billion gallons to 13.3 billion gallons. As shown in Figure 1, the percentage of U.S. corn harvest diverted to ethanol production has steadily increased from less than 10 percent to over 40 percent. Over the same period, the real corn price received by farmers has more doubled. Other crop prices have also increased, as cropland has been reallocated in response to rising prices and the potential for larger returns.

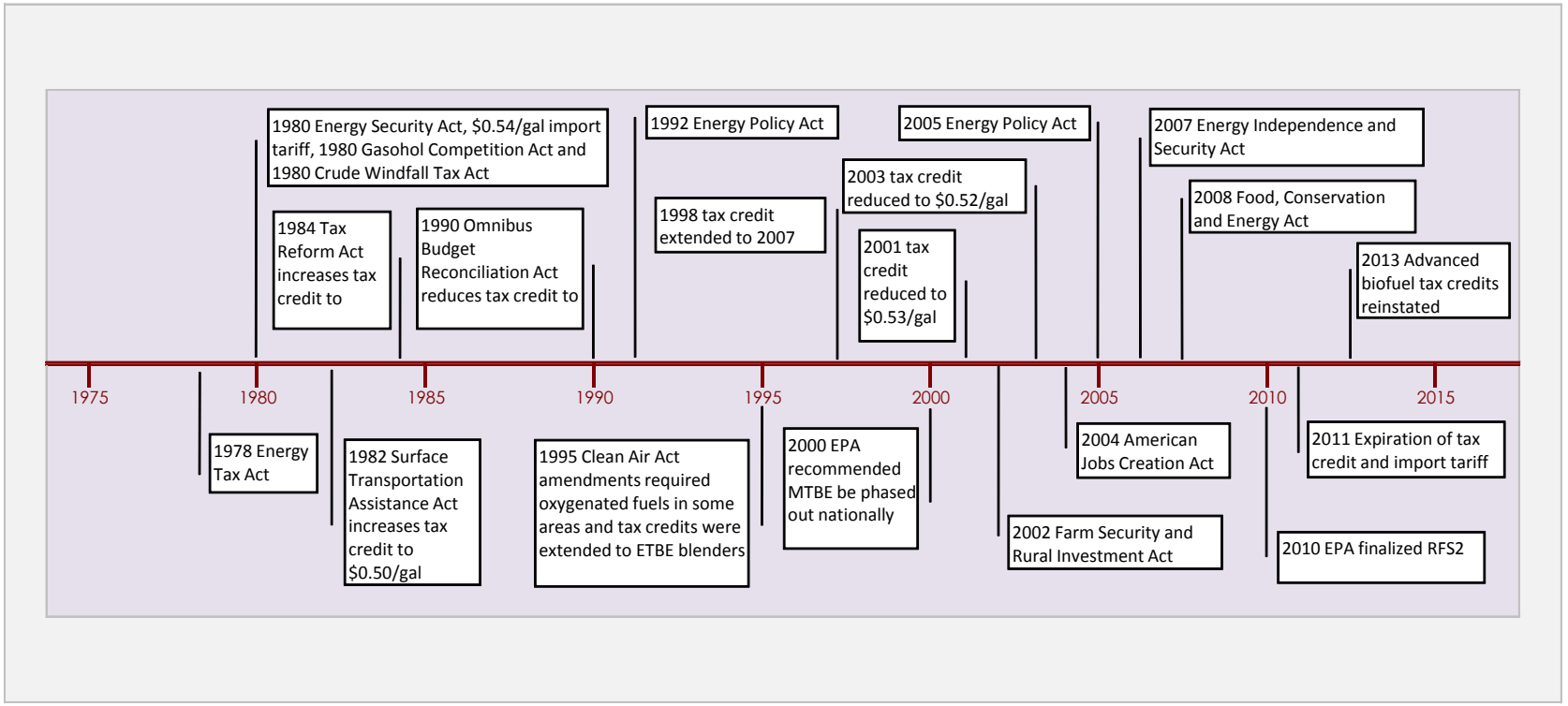
Figure 1: Annual Corn Prices and Percent Corn Production Used for Ethanol



Source: USDA Economic Research Service Feed Grains Database (USDA 2013b)

The rapid increase in food prices from 2006 to 2008 coincided with a dramatic expansion of the U.S. Renewable Fuel Standard (RFS), highlighting the blending mandate as a potential driver of short-and longer-term price trends. However, the RFS was only the latest in a series of policies promoting renewable fuels in the United States stretching back three decades. The U.S. ethanol policy timeline (Figure 2) illustrates the policy changes that have occurred over the last 35 years. Marking the beginning of U.S. biofuel policy support, the 1978 Energy Tax Act included a $0.45 tax credit for fuels at least 10 percent ethanol by volume. The Energy and Security Act of 1980 provided incentives for ethanol producers in the form of insured loans, price guarantees and purchase agreements. In the same year, Congress levied a $0.54/gal import tariff and passed the 1980 Gasohol Competition Act, which banned retaliation against ethanol retailers. The 1980 Crude Windfall Tax Act extended the ethanol-gasoline blend tax credit. The size of subsidies steadily increased due to additional legislation in the 1980s. The 1992 Energy Policy Act defined blends with 85 percent ethanol as alternative transportation fuels and set requirements and tax credits for the adoption of alternative fuel vehicles. The ethanol industry was further strengthened during the 1990s and 2000s due to oxygenate mandates for gasoline and state-level bans of methyl tert-butyl ether (MTBE). The Farm Security and Rural Investment Act (or Farm Bill) of 2002 provided additional support to the industry by creating support programs and allocating funding for research and development of biomass energy projects. The American Jobs Creation Act of 2004 consolidated existing tax credits under the volumetric ethanol excise tax credit.

Figure 2: History of U.S. Ethanol Policy



The 2005 Energy Policy Act established the Renewable Fuel Standard (RFS), which mandated blending 7.5 billion gallons of renewable fuel with gasoline annually by 2012. The Energy Independence and Security Act (EISA) of 2007 expanded these requirements, setting a target of 36 billion gallons of biofuels to be produced or imported by the United States annually by 2022, and establishing greenhouse gas (GHG) reduction criteria and life-cycle assessment guidelines. This updated Renewable Fuel Standard (referred to as RFS2) divided renewable fuels into four different categories based on feedstock and GHG reductions and set specific targets for cellulosic and other advanced biofuels. For instance, corn ethanol can be used to satisfy up to 15 billion gallons of the biofuels mandate starting in 2015. The Food, Conservation and Energy Act (2008 Farm Bill) extended the import tariff, reduced the corn-based ethanol tax credit, and increased the tax credit for cellulosic ethanol blends. In 2010, the EPA finalized regulations to implement the RFS2 program. The ethanol production tax credit and the import tariff expired at the end of 2011 (though cellulosic biofuel and biodiesel tax credits were temporarily extended in 2013), establishing production mandates as the principal government support system for a growing U.S. biofuel industry.

Unless crop production is perfectly elastic, diversion of some portion of the corn harvest for use as biofuel feedstock is bound to put upward pressure on crop prices. However, a correlation between biofuel production and crop prices is not sufficient to infer a causal relationship or to parse the exact contribution of biofuels to food price increases. As food prices spiked in 2008, researchers increasingly turned their attention toward this question.[3]

A slew of studies from the academic and gray literatures in 2008 and 2009 contributed to the debate about rising food prices (Timilsina and Shrestha 2010). Studies from this period ranged from qualitative discussions to back-of-the-envelope calculations to formal quantitative exercises using partial or general equilibrium economic models. While the potential role of biofuels garnered considerable attention, the literature identified several other contributors to the food price spike on both the demand and supply sides. They included rising food demand due to higher population and income levels in developing countries, drought in major exporting countries, trade restrictions, devaluation of

[3] Another controversy surrounding biofuels is their greenhouse gas (GHG) impact, accounting for indirect market-driven factors like land use change. An extensive literature has developed around this question since 2008, starting with Searchinger et al. (2008). We do not address the issue of biofuel GHG emissions in this paper, except to note that a lower land supply elasticity would tend to minimize GHG emissions due to the clearing of native vegetation but also lead to steeper crop price increases in response to biofuel expansion. Several studies whose main focus is estimating the lifecycle GHGs associated with biofuel production also produce estimates of crop price impacts that we included in our review of long-run studies.

the U.S. dollar, and speculation in commodity markets (Abbott, Hurt & Tyner 2009, Collins 2008, Mitchell 2008, Trostle 2008).

The price of energy also received significant attention for contributing to higher food prices, though it is difficult to isolate its effect from that of biofuel production. Oil prices reached $133 per barrel at the peak of the commodity price rise in July 2008, an increase of 94 percent from 2007. Oil prices increase the price of food directly by pushing up the cost of inputs like petroleum-based fertilizer and indirectly by making biofuels more competitive with gasoline, spurring diversion of crop feedstocks from food to fuel (Baffes & Haniotis 2010). Tenenbaum (2008) highlights the connection between food prices and oil prices, suggesting that high oil prices may intensify competition between these commodities. In response to a request by Texas to partially waive the RFS2 requirements, EPA (2008) found that the mandate was likely not binding because high oil prices increased demand for ethanol even absent the mandate. This result demonstrates that biofuel production need not always be policy-driven; market forces can also stimulate demand.

Despite some agreement about the collection of factors responsible for increasing food prices in 2008, the literature has yielded wildly disparate estimates for the magnitude of the effect caused by biofuels. The National Research Council's (2011) report on the Renewable Fuel Standard presents estimates for the contribution of biofuels to the increase in corn prices during 2007-2009 from nine studies, with results ranging from 17 percent to 70 percent.[4] Although these analyses purportedly address a single policy question, a closer look reveals that they do not yield an apples-to-apples comparison. Besides using distinct analytic approaches, the studies examine different policy instruments, different world regions' biofuel targets, and even different timeframes within the 2007-2009 period. These factors, as well as assumptions about demand and supply elasticities and whether indirect effects are included, can have a large effect on the results (Baier et al. 2009). A 2009 review of nine biofuel expansion studies (Zhang et al. 2009a) examines the reasons why the range in estimated food price impacts is so large. The authors identify several potentially important differences, including modeling structure, international trade, co-products, land supply elasticity, and energy market assumptions. However, they stop short of any quantitative analysis to parse the relative importance of these factors in driving the results.

[4] The NRC report includes two additional studies (Banse et al. 2008 and Fischer et al. 2009) in its review that are not comparable because they present estimates of the aggregate increase in crop prices due to biofuels relative to a lower- or no-biofuels reference scenario rather than estimates of the proportion of the total increase in crop prices due to biofuels.

The National Research Council (2011) also makes the important point that crop price increases do not translate into commensurate changes in retail food prices. They find that a 20 to 40 percent rise in corn prices would cause a 1 to 2 percent increase in the retail price of grocery food items. Babcock (2010) asserts that the price of corn is one of the most important factors in determining the cost of livestock and related products, because it serves as a reference price for other key carbohydrate sources, such as barley and wheat. However, Baier et al. (2009) note that the prices for processed goods are driven more by labor, packaging, marketing and transport costs than by the raw commodity prices. Crop price changes are likely to have bigger impacts on consumers in developing countries because they typically rely more heavily on raw agricultural products and spend a greater portion of their incomes on staple foods (Roberts and Schlenker 2013; Zhang et al., 2009a; Runge and Senauer, 2007).

In the next section of our paper, we take a systematic look at the factors that account for the wide range in biofuel impacts on crop prices. While the studies mentioned above take a retrospective look at the period surrounding food price spikes in 2008, we focus instead on prospective analyses of the effect of biofuel policies on commodity prices in the long run.

3. Long-Run Effects of U.S. Ethanol Expansion on Corn Prices

Recent years have seen a proliferation of studies projecting long-run effects of biofuel expansion on commodity markets. Such studies can help anticipate average impacts in the future, accounting for likely market responses and technological progress, but they can also mask the potential for short-term fluctuations that could adversely affect food security. This section reviews recent estimates of the long-term impact of biofuel expansion on agricultural commodity prices. We examine a few different measures of the estimated price impact, including both absolute and normalized price changes, to assess the range of projected impacts. We also conduct a meta-analysis to consider several factors that may drive the differences in results across studies.

We limit our review to studies that estimate the impact of U.S. corn ethanol expansion on corn prices (or a close proxy for corn prices such as grain prices) by comparing a business-as-usual baseline with one or more policy scenarios. While long-run analyses have considered biofuels in different world regions, the effects of increased U.S. corn ethanol production have garnered particular attention. Most of the studies identified examine the EISA Renewable Fuels Standard (RFS2) as a main driver of ethanol

expansion, but some also consider growth fueled by other domestic or international policies or market forces.[5]

We identified relevant studies by searching academic databases including EconLit and Google Scholar, as well as checking the references of already-identified studies. We limit our review to original quantitative analyses such as econometric analyses or computable equilibrium model simulations that estimate changes in grain prices and ethanol production levels.[6] As noted above, we focus here on long-run studies that implicitly or explicitly allow markets time to adjust to new policy and market signals. Empirical estimates of short-run impacts are discussed in section 4. Because of the desire to reflect the most recent research, we include journal articles, reports from government agencies or international organizations, and working papers completed between 2008 and 2013 in our review. This time period is highly relevant for understanding the impacts of current policy, as the ramp up of renewable fuel requirements included in EISA began in 2008. When multiple studies from a research group use the same model and similar baseline and policy scenarios, we select only one for inclusion; in this case, we prioritize journal articles, analyses focusing on RFS2 as a driver of biofuel expansion, and the most recent working paper if a journal article does not exist.

We identify 18 studies meeting these criteria. They include 12 journal articles, three working papers, and three government or international organization reports. Several studies examine multiple scenarios, yielding a total of 78 estimates. Seventy of these represent corn ethanol expansion scenarios, while eight of them examine a decrease in corn ethanol production.

Table 1 lists the studies and reports the range of price changes estimated in the 70 corn ethanol expansion scenarios. An initial glance reveals a striking range of estimates. At the high end, Rosegrant et al. (2008) project that doubling RFS2 and other world biofuel policy targets would raise corn prices by 72 percent relative to business-as-usual, while at the low end, Mosnier et al. (2013) estimate that increasing the RFS2 mandate up to 50 percent in the year 2030 would have no effect on corn prices. Even when we focus on the 34 scenarios that examine RFS2 alone, holding constant other policy and market drivers, the range of price effects spans an order of magnitude—from three percent (U.S. EPA 2010 and Gehlhar et al. 2010) to 71 percent (Tyner et al. 2010). This variation is similar to the range reported in other reviews such as Zhang et al. (2009a) and National Research Council (2011).

[5] While we include studies that examined biofuel policies in other world regions *in addition* to the U.S., we exclude studies primarily focusing on other world regions (e.g., Banse et al. 2008, who focus on the EU, and Timilsina et al. 2012, who assess potential global production, of which US production makes up less than one percent).

[6] In a few cases, we obtained information about price effects directly from the study authors when it was not reported in the paper (Anderson and Coble 2010, Chakravorty et al. 2012, Hertel et al. 2010 and Tyner et al. 2010).

Table 1. Long-Run Studies Estimating Impact of U.S. Corn Ethanol Expansion on Corn Prices

Study	Model	Number of ethanol expansion scenarios	Policy instrument	Corn price change*
Journal articles				
Anderson & Coble	Probabilistic supply and demand model	1	RFS2	7%
Chen & Khanna	BEPAM	6	RFS2, tax credits, and import tariffs	24% - 52%
Cui et al.	Multi-market model	5	RFS2; other optimal and suboptimal biofuel policies	17% - 44%
Fernandez-Cornejo et al.	FARM II	2	RFS2 & Brazilian ethanol policy	23%
Hayes et al.	FAPRI	2	RFS2, tax credits, and import tariffs	19% - 22%
Hertel et al.	GTAP-BIO	2	RFS2	16% - 18%
Huang et al.	CAPSiM-GTAP	2	RFS2, EU, and Brazilian biofuel policy; market-driven expansion	15% - 50%
Mosnier et al.	GLOBIOM	8	Deviations from RFS2	0% - 13%
Roberts & Schlenker	Supply and demand model	2	RFS2	20% - 30%
Rosegrant et al.	IMPACT	2	RFS2, EU, and Brazilian biofuel policy; doubling existing targets	26% - 72%
Thompson et al.	FAPRI-MU	1	RFS2	8%
Tyner et al.	Partial equilibrium model	14	RFS2, fixed and variables subsidies	7% - 71%
Working papers				
Bento et al.	Dynamic multi-market model	4	RFS2, tax credits	12% - 25%
Chakravorty et al.	Dynamic multi-market model	1	RFS2, EU, and middle-income country biofuel policy	19%
Roberts & Tran	Competitive storage model	9	RFS2	14% - 44%
Government/international organization reports				
OECD-FAO	AGLINK-COSIMO	1	RFS2 and EU biofuel policy; removal of policy support	6%
Gehlhar et al.	USAGE	6	RFS2	3% - 5%
U.S. EPA	FAPRI, FASOM	2	RFS2	3% - 8%

* Five studies examine the price change of a commodity other than corn: Chakrovorty et al. (2012) examine cereals, OECD-FAO (2008) and Hertel et al. (2010) use coarse grains (which is comprised primarily of corn), and Roberts and Schlenker (2013) and Roberts and Tran (2012) use a calorie-weighted average of corn, soy, rice, and wheat.

What could account for such divergent estimates of crop price impacts from the same policy? Each study and scenario varies along many dimensions, from assumptions about international biofuel policies to the year for which projections are made. Zhang et al.'s (2009) literature review highlights model structure, land supply assumptions, international trade, co-products, scenario design, agriculture-fuel market linkages, crude oil price assumptions, and the elasticity of substitution between biofuels and petroleum as key assumptions but does not isolate the contribution of each to the price impact of biofuels on agricultural commodities. We more formally investigate the role that some of these (and other) factors play in our meta-analysis, though we were unable to find information on every factor for every study in our review.

Table 2 provides summary information for several factors that we were able to quantify across most or all of the studies.[7] The first of these is modeling approach. Most studies use computable equilibrium models, whether partial equilibrium (PE) or general equilibrium (GE) models. PE models analyze the impact of a policy change on one or more markets and do not take into account all sectors in a given economy. PE models are sometimes criticized for their inability to control for interactions between all related markets or fully account for aggregate economic effects, but they are particularly useful for investigating discrete relationships that might otherwise be missed in models designed to consider macroeconomic implications. In contrast, GE models simulate all interconnected markets in the economy. One drawback of GE applications in biofuel analysis is that they are highly aggregate representations of the economy, such that important details of the agriculture and energy sectors are sometimes omitted, but GE models have represented the bioenergy sector with varying degrees of detail (Kretschmer and Peterson 2010). GE models also tend to use larger implicit supply elasticities than PE models (Kretschmer and Peterson 2010).

Of the studies in this review, four use GE models and fourteen use PE models. Among the GE studies, Hertel et al. (2010) use the GTAP-BIO global trade model, which includes land cover data corresponding to 18 agro-ecological zones, to estimate the effects of RFS2 on global land use and GHG emissions while considering market-driven responses in food demand and crop yields. Huang et al. (2012) use a similar GTAP-based CGE model updated to incorporate the biofuels sector to estimate the price effects of global biofuel expansion due to mandates and market conditions.[8] Fernandez-Cornejo et al. (2008) apply FARM II, a USDA-developed CGE model linked with land cover and climatic data for

[7] The Appendix provides the full set of variables for all 78 scenarios.

[8] The authors also use CAPSiM, a PE model of the Chinese agricultural sector, to examine the implications for income and agricultural production in China. The CAPSiM portion of the analysis is excluded from our review of long-run studies due to its non-US focus but is discussed in the section on food security.

different agro-ecological zones, to assess the impacts of RFS2 and Brazilian sugarcane ethanol production under different crop yield growth assumptions.[9] A USDA Economic Research Service report by Gehlhar et al. (2010) examines the effects of RFS2 under different assumptions about oil prices and biofuel tax credits using USAGE, a CGE model updated to include biofuels.

Turning to the PE studies, most rely on detailed models of agricultural markets that capture interactions across commodities. Rosegrant et al. (2008) examine the effects of both continuing and doubling global biofuel policy targets using IMPACT, a global PE model of the agricultural sector. Tyner et al. (2010) use a PE model to estimate the effects of RFS2 and other biofuel subsidies under varying oil price assumptions. OECD-FAO (2008) assesses the impacts of world biofuel expansion (including the pre-EISA RFS) using the Aglink-Cosimo modeling system. The Food and Agriculture Policy Research Institute (FAPRI) model, a PE model with detailed representations of domestic and international agriculture and ethanol markets, is used by Hayes et al. (2009) to examine the effect of RFS2 and biofuel tax credits under different oil prices. U.S. EPA (2010) also uses the FAPRI model in its Regulatory Impact Assessment for RFS2, as well as using the Forest and Agricultural Sector Optimization Model (FASOM), a dynamic model of U.S. agriculture and forestry, as an alternative approach. (Beach and McCarl 2010 provide a description of the FASOM approach.) Thompson et al. (2009) apply FAPRI-MU, a subset of the FAPRI model maintained at the University of Missouri that focuses on domestic markets, to conduct a stochastic analysis of the effects of corn and oil market shocks on biofuels with and without RFS2. Mosnier et al. (2013) examine scaling RFS2 up or down using the Global Biosphere Management Model (GLOBIOM), an international model of land-based sectors including agriculture, forestry, and bioenergy.

A few recent working papers use multi-market models that integrate agriculture and fuel markets. Chakravorty et al. (2012) use a dynamic PE model with endogenous land allocation to examine the effect of RFS2, EU, and middle-income countries' biofuel targets on world food prices and GHG emissions. Chen and Khanna (2013) use the Biofuel and Environmental Policy Analysis Model (BEPAM), a dynamic non-linear programming model of agricultural and fuel markets, to study RFS2, biofuel tax credits and import tariffs under varying assumptions about imported sugarcane ethanol supply. Bento et al. (2012) also use a dynamic multi-market model of land, food, and fuel markets to examine net GHG impacts of RFS2 with and without volumetric tax credits. Cui et al. (2011) construct a highly stylized model of U.S. corn and petroleum markets to assess a variety of biofuel policies, including RFS2 and alternative fuel tax and biofuel subsidy combinations.

[9] Fernandez-Cornejo et al. (2008) construct a baseline that is not a true business-as-usual projection because it holds yields constant at 2005/06 levels. Thus, the policy scenarios encompass changes in both yields and biofuel targets.

The three remaining studies do not use detailed computable equilibrium models of the agriculture sector and instead conduct relatively simplified PE analyses of crop supply and demand that do not model interactions among agricultural commodities. However, they all involve original analysis beyond a simple application of supply and demand elasticities that warrants inclusion in our review. Roberts and Schlenker (2013) conduct an econometric analysis using weather shocks to estimate crop supply and demand elasticities and then apply them to calculate commodity price effects of biofuel expansion. Roberts & Tran (2012) use a competitive storage model to estimate the effects of RFS2 on world food prices as a function of how much time markets have to adjust to the policy.[10] Anderson & Coble (2010) estimate the price impacts of RFS2 using a rational expectations framework that accounts for the stochastic nature of supply and demand shocks.

Table 2. Key Variations across Long-Run Ethanol Studies

	Mean*	Std. dev.	Min	Max	Obs
GE model (1 = yes, 0 = no)	22%	0.42	0	1	78
Baseline corn ethanol (bgal)	7.60	4.46	0	20.6	78
Policy scenario corn ethanol (bgal)	15.58	5.99	0	40	78
Ethanol co-products included (1 = yes, 0 = no)	77%	0.42	0	1	78
Year †	2016	6.07	2006	2030	78
Baseline crude oil price ($)	89.0	24.90	40	160	39
Cellulosic ethanol increase (bgal)‡	14.63	6.41	0.22	22.56	31
US biodiesel increase (bgal)‡	1.20	0.51	0.16	2	14
EU biodiesel increase (bgal)‡§	3.55	2.80	1.4	6.95	4
Other international biofuel increase (bgal)‡§	4.42	3.81	0.83	13.01	19
Corn (vs. aggregate commodity) (1 = yes, 0 = no)	72%	0.45	0	1	78
RFS2 policy scenario (1 = yes, 0 = no)	46%	0.50	0	1	78

*Each study is given equal weight when calculating the mean and standard deviation to avoid giving more weight to studies with a greater number of scenarios.

† OECD-FAO reports results for a 2013-2017 average; we use 2015 in the analysis.

‡ Summary statistics for non-US corn ethanol biofuel quantities are only given here for those studies with a positive quantity of each biofuel category.

§ Rosegrant et al. includes increases in feedstocks for EU biodiesel and other international biofuels, but insufficient information is available to convert feedstock quantities into biofuel volumes, so the Rosegrant et al. quantities are not included here. In the meta-analysis that follows, EU biodiesel and other international biofuel increases are estimated for the Rosegrant et al. "expansion" scenario by averaging the increases of each respective biofuel from other studies that model EU and other international policies. For the "drastic expansion" scenario, these quantities are doubled.

[10] In this section, we focus on the long-term equilibrium price results estimated by Roberts and Tran. In the next section, we discuss the paper's estimated short-term price effects when the policy shock is unanticipated.

The different objectives of the studies just described suggest that their baseline and policy scenario corn ethanol production levels vary considerably. Even though several studies model the RFS2, which calls for 15 billion gallons of renewable fuels (most likely corn ethanol) starting in 2015, there are large differences in baseline corn ethanol volumes, leading to different estimates of the expansion in production needed to achieve the mandate. For instance, U.S. EPA (2010) projects 12 billion gallons of corn ethanol under business-as-usual conditions. In contrast, Tyner et al.'s (2010) $40 per barrel oil scenario yields no ethanol without the mandate. These studies estimate baseline corn ethanol production endogenously as a function of oil prices, crop yields, and other parameters. Other studies fix the baseline exogenously, typically based on production in a recent year (e.g., Gehlhar et al. 2010, Roberts and Tran 2012). Some of these studies include scenarios that go beyond the RFS2 mandate to examine the impacts of more aggressive expansion. For example, Rosegrant et al. (2008) examine the effects of doubling current U.S. and global biofuel targets, leading to approximately 28 billion gallons of corn ethanol.[11] Mosnier et al. (2013) take RFS2 as the baseline and consider the effects of increasing or decreasing the mandate.

Another relevant assumption is the treatment of ethanol co-products. Distillers' dried grains (DDGs) are a joint output of the ethanol production process that can be used as animal feed, mitigating some of the effect of higher grain prices on the livestock industry. Corn oil is another potential output that could itself be used to produce biodiesel. Due to our focus on recent studies, most analyses account for at least the DDG co-product, but three of the earlier studies do not (Rosegrant et al. 2008, Fernandez-Cornejo 2008, Anderson and Coble 2010). Roberts and Schlenker (2013) and Roberts and Tran (2012) consider scenarios with and without recycling one-third of the calories of corn ethanol as livestock feed.

The projection year for which price impacts are reported is another difference across studies, with several studies estimating results out to the year 2020 or beyond, and others holding conditions at status quo levels except for the biofuel policy shock. The projection year has important implications for crop yields, since most studies assume steady improvement in crop yields over time, thus lessening competitive pressure for land in the future. Some studies use USDA projections to estimate future crop yield gains (e.g., U.S. EPA 2010), while others implicitly hold yields constant at current levels (e.g., Roberts and Schlenker 2013, Tyner et al. 2010). Some analyses also allow endogenous crop yield changes in response to the policy (e.g., Hertel et al. 2010). While crop yield is a key assumption that

[11] Rosegrant et al.'s paper presents tons of biofuel feedstock rather than liquid biofuel volumes. We estimated the corresponding biofuel volumes using the assumption that 1 bushel of corn yields 2.77 gallons of biofuel (http://www.fapri.missouri.edu/outreach/publications/2006/biofuelconversions.pdf).

could affect the price impacts from biofuel production, it was not reported in most studies, so it is not included in our dataset.[12] Instead, the projection year serves as a proxy for anticipated yield and other technological improvements. In the next section on short-run price impacts, we discuss the impact of drought conditions that sharply curtail yields.

Oil prices are a key determinant of ethanol production, particularly in the baseline. Both the general equilibrium and multi-market partial equilibrium model studies estimate oil prices in the policy scenario endogenously. In Huang et al.'s (2012) study, a doubling of oil prices from $60 per barrel in the baseline to $120 per barrel in the market-driven expansion scenario leads to an eightfold increase in corn ethanol, making the government mandate non-binding. Tyner et al. (2010) find that oil price assumptions have a large effect on baseline ethanol production, and hence the impact of RFS2 and other biofuel policies on ethanol expansion. Gehlhar et al. (2010) vary oil price assumptions as well but exogenously impose the level of corn ethanol production in both the baseline and policy scenarios, muffling the effect of oil prices on production levels. Half of the studies in our review report oil prices. The elasticity of substitution between biofuels and oil is still another potentially important factor. If studies assume that technical barriers to increased substitutability of biofuels for petroleum such as the ethanol "blend wall" are overcome, then projections for ethanol expansion would likely be higher.[13] However, the elasticity of substitution is not in our dataset because very few studies report this information.

Another important difference across studies is their representation of biofuels produced from feedstocks other than corn ethanol. Eight of the 18 studies in our review focus solely on changes in US corn ethanol production. The remaining studies also consider increases in other biofuels between the baseline and policy scenarios. Most include increases in biodiesel, cellulosic ethanol, or other advanced biofuels resulting from the RFS2 (either domestic or imported). Six of these studies also model biofuel expansion resulting from other world regions' policies, including the EU, Brazil, and other middle-income countries. It is difficult to disentangle the effect of U.S. corn ethanol production on corn prices in studies that model increases in other types of biofuels. Demand for other biofuel feedstocks could raise corn prices indirectly, even in the case of non-food feedstocks, which could still heighten competitive pressures for cropland. Price effects in these studies should not be attributed solely to U.S. corn ethanol

[12] The fact that some studies aggregate multiple crops could make yield assumptions difficult to compare as well.
[13] The term "blend wall" refers to the maximum amount of ethanol that can be blended into the fuel supply due to technical and regulatory constraints. Federal regulations do not currently allow use of ethanol blends exceeding ten percent in conventional vehicles manufactured before 2001.

expansion. In addition, inclusion of advanced technologies like cellulosic ethanol in the modeling framework could serve as a proxy for technological progress.

The elasticity of demand for food is an assumption that could have important implications for price impacts but is only reported in a few studies and is therefore excluded from our dataset. A few studies that highlight the elasticity of demand find that the impact of biofuels on crop prices rises if demand for food is less elastic (Hertel et al. 2010, Roberts and Tran 2012). Roberts and Schlenker (2013) derive new estimates for the elasticity of demand for food calories from corn, soy, rice, and wheat ranging from -0.05 to -0.08, though the demand for corn alone is likely to be more elastic since the weighted food metric includes corn's major substitutes.

As already mentioned, most, but not all, studies focus on corn prices, but a few examine a more aggregate measure such as cereals. Of the studies that focus on corn, eight of these report actual prices from the baseline and policy scenarios, whereas the remaining studies only give percent changes in price in the policy scenario relative to the baseline. Over half of the scenarios project the effects of the RFS2 alone, while the remaining scenarios examine other domestic and international biofuel policies separately or in combination with RFS2. Some of the RFS2-only studies focus solely on the corn ethanol requirement, while others model mandated increases in other biofuel types as well.

Normalized Corn Price Impacts

In our view, the differences in the magnitude of the change in corn ethanol production (i.e., the differences in volume between the policy and baseline scenarios) create the most fundamental obstacle to comparing results across studies. For instance, the divergence in price impacts from RFS2 estimated by U.S. EPA (2010) and under the Tyner et al. (2010) $40 per barrel oil price scenarios is unsurprising considering that they anticipate vastly different increases in the level of ethanol production (2.7 billion gallons and 15 billion gallons, respectively). In effect, the price impacts reported in Table 1 conflate changes in ethanol production levels and changes in corn prices per unit of ethanol expansion.

One way to make the results more comparable across studies is to examine the change in corn price while controlling for the change in corn ethanol production. We do this by converting the results from each study into two common metrics: the percent change in corn price per billion-gallon increase in corn ethanol (a semi-elasticity measure), and the percent change in corn price per percentage point increase in corn ethanol (an elasticity measure). In other words, we normalize the change in prices by the change in ethanol quantity, where the latter is measured in either volumetric or percentage terms.

Table 3 presents the normalized corn price results compared with the absolute price changes across all scenarios in each study (including scenarios that model a *decrease* in corn ethanol, accounting for a negative price change). It shows that once we isolate the price effect of biofuels expansion while holding the level of expansion constant, the range of estimates within each study shrinks greatly even when the absolute price differences are sizable. For example, the 7 to 71 percent absolute price impact range estimated by Tyner et al. shrinks to a 3 to 5 percent increase per billion gallons of ethanol production. Similarly, Rosegrant et al.'s range of 26 to 72 percent narrows to an estimate of 2.5 to 2.9 percent per billion gallons. Across most of the studies, the range of price effects spans only one or two percentage points. A similar result holds for the percent price change per percentage increase in corn ethanol production; the effects fall within a relatively narrow band. This narrowing of estimates confirms that a large portion of the variation in reported price effects from ethanol production stems from the differences in corn ethanol volumes examined within studies.

Table 3. Long-Run Impact of Corn Ethanol on Absolute and Normalized Corn Prices

Study	Absolute price change	Price change per billion gallon increase in ethanol	Price change per 1% increase in ethanol
Anderson & Coble	7.0%	7.0%	0.60%
Bento et al.	12% - 25%	7.8% - 8.4%	0.90% - 1.0%
Chakravorty et al.	19%	2.3%	0.16%
Chen & Khanna	24% - 52%	3.1% - 5.7%	0.12% - 0.22%
Cui et al.	-23% - 44%	2.2% - 3.9%	0.13% - 0.23%
Fernandez-Cornejo et al.	23%	2.3%	0.10%
Gehlhar et al.	3.1% - 4.8%	0.5% - 0.7%	0.04% - 0.05%
Hayes et al.	19% - 22%	2.2% - 2.9%	0.27% - 0.36%
Hertel et al.	16% - 18%	1.2% - 1.3%	0.20%
Huang et al.	15% - 50%	1.4% - 1.5%	0.07%
Mosnier et al.	-7% - 13%	-0.27% - 1.9%	-0.04% - 0.26%
OECD-FAO	-5% - 6%	1.94% - 2.07%	0.23% - 0.25%
Roberts & Schlenker	20% - 30%	1.8% - 2.7%	*
Roberts & Tran	14% - 44%	1.3% - 4.0%	0.05% - 0.15%
Rosegrant et al.	26% - 72%	2.5% - 2.9%	0.10% - 0.11%
Thompson et al.	7.6%	1.6%	0.21%
Tyner et al.	7% - 71%	3.4% - 4.8%	0.05% - 0.8%
U.S. EPA	3.4% - 8.4%	1.3% - 3.1%	0.15% - 0.38%
Study-weighted average	19.3%	2.9%	0.24%

*Roberts & Schlenker use a baseline of no corn ethanol production, so we cannot calculate a price change per percentage increase in ethanol.

The range of estimates *across* studies is still substantial, however, even when considering normalized price changes. On the low end, Mosnier et al. (2013) report a counterintuitive finding that lowering the RFS2 mandate to 75 percent of its target level would result in a slight *increase* in corn prices in the year 2030 (i.e., a negative normalized price impact), while expanding the RFS2 to 125 or 150 percent of established levels would have no effect on corn prices. Bento et al. (2012) estimate the highest normalized price impact—an increase in corn prices of around 8 percent per billion gallon increase in corn ethanol production (or alternately, a 1 percent increase in corn prices per percent increase in corn ethanol) in 2012 and 2015. Taking the study-weighted average across all scenarios, each billion gallon increase in corn ethanol raises corn prices by 2.9 percent. Similarly, a 10 percent expansion in corn ethanol production increases corn prices by an average of 2.4 percent.[14]

Meta-Analysis of Ethanol's Impact on Corn Prices

Given the wide range of normalized price effects, it is clear that ethanol production levels do not fully explain the differences among estimates. We conduct a meta-analysis to investigate the remaining sources of variation in estimated corn price impacts. We consider the three different outcome variables reported in Table 3: the absolute price change, the price change per billion gallons of corn ethanol, and the price change per percentage point increase in corn ethanol. We include as potential explanatory variables the baseline and policy scenario corn ethanol volumes; inclusion of ethanol co-products; projection year; increases in the volumes of cellulosic biofuels, US biodiesel, EU biodiesel, and other international biofuels; whether corn is the modeled commodity (versus a more aggregate crop commodity); and whether the RFS2 is the only policy instrument. We exclude oil price because it is unavailable for several studies, but we examine its effect in a sensitivity analysis discussed at the end of the section.

For the two normalized price metrics, we estimate a random effects model to address the fact that estimates produced by the same study are not independent (Nelson and Kennedy 2009). A Breusch-Pagan Lagrange multiplier test indicates that study-level random effects are jointly significant in both equations ($p < 0.001$). For the absolute price change equation, a Breusch-Pagan test indicates that random effects are not significant ($p = 0.53$), so we instead estimate a weighted least squares model to

[14] The study-weighted average raw price impact of 19.3% is not very meaningful, given the wide range of scenarios considered. A more useful statistic is the raw price impact across those scenarios estimating the effect of the RFS2 alone, which is 16.7%.

give each study equal weight.[15] We cluster the standard errors by study in all three equations to address heteroskedasticity (Nelson and Kennedy 2009).[16] It is not possible to estimate the equations using study fixed effects because several attributes (e.g., model structure) only vary at the study level.

Table 4. Long-run Corn Price Responsiveness to Biofuels Expansion: Meta-Regression Results

	Absolute price change	Price change per billion gallon increase	Price change per percentage increase
GE model	-0.169***	-0.0253***	-0.000785
	(0.0219)	(0.00651)	(0.000722)
Baseline corn ethanol (bgal)	-0.0298***	-0.000267*	0.000375***
	(0.00307)	(0.000139)	(1.15e-05)
Policy corn ethanol (bgal)	0.0199***	-0.000122	-1.21e-05
	(0.00452)	(0.000222)	(1.21e-05)
Projection year	-0.00285	-0.000846***	-0.000138***
	(0.00296)	(0.000187)	(2.54e-05)
Co-products included	-0.0255	-0.0132***	-0.000601***
	(0.0318)	(0.00170)	(3.32e-05)
Cellulosic biofuels (bgal)	0.00146	0.000323	2.76e-05
	(0.00205)	(0.000316)	(4.52e-05)
US biodiesel (bgal)	0.00862	-0.00497	8.01e-05
	(0.0215)	(0.00375)	(0.000696)
EU biodiesel (bgal)	-0.0180	0.000539	-0.000114
	(0.0107)	(0.00153)	(0.000265)
Other international biofuels (bgal)	0.00621	0.00162*	9.37e-05***
	(0.00779)	(0.000864)	(2.15e-05)
Corn (vs. aggregate commodity)	0.0848***	0.0131*	0.000556
	(0.0194)	(0.00671)	(0.000706)
RFS2 policy scenario	-0.0406**	0.00157***	2.40e-05
	(0.0160)	(0.000505)	(8.04e-05)
Constant	5.869	1.739***	0.277***
	(5.939)	(0.376)	(0.0511)
Observations	78	78	73
R-squared	0.82	0.40	0.38
within R-squared		0.52	0.90
between R-squared		0.39	0.40

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

[15] A common practice in meta-analysis is to weight by the inverse of the variance of the effect size to give more weight to more precise estimates (Nelson and Kennedy 2009). However, the estimates in our study are derived from equilibrium simulation models rather than econometric models (with the exception of Roberts and Schlenker), so estimates of variance or proxies such as sample size are not available.

[16] Because Hayes et al. (2009) and U.S. EPA (2010) both use the FAPRI model, an alternate grouping for random effects and clusters would be by model rather than by study. Grouping by model has minor effects on the results.

Table 4 reports the meta-regression results for all three measures of corn price change. The factors we are able to quantify across all studies explain a sizable portion of the variation across estimated price effects, as indicated by R-squared statistics of at least 0.38. For the regression using the absolute corn price change (i.e., not normalizing by ethanol volume), the meta-regression explains 82 percent of the variation in estimates. In the two random effects equations, the independent variables explain more of the variation within studies than between studies.

Turning to the explanatory variables, one striking result is the importance of modeling framework. Across all three price metrics, studies using general equilibrium models estimate smaller price effects, and the effect is statistically significant in the first two equations. For example, GE estimates of price change per billion gallons of corn ethanol are about two and a half percentage points lower than PE estimates. This result makes sense intuitively considering that GE models typically use larger implicit supply elasticities than PE models (Kretschmer and Peterson 2010), and they also allow for adjustments in resource allocation across all markets in the economy, which can lessen impacts in the directly affected sector.

Baseline and policy corn ethanol production levels are also extremely important in determining absolute corn price changes. Smaller baseline and larger policy scenario production—amounting to a larger increase in volume—are associated with significantly higher absolute price changes. The effect is not entirely symmetric; a one billion gallon increase in policy scenario corn ethanol has a smaller effect than a one billion gallon decrease in baseline corn ethanol, all else equal.[17] Policy and baseline corn ethanol are also included in the normalized price impact equations to see if there are non-linearities in this effect (similar to including squared terms in the absolute price change equation). The results show that baseline corn ethanol is a significant predictor of price change per billion gallon expansion, indicating that studies with higher baseline ethanol production find lower proportionate impacts on corn prices. Baseline corn ethanol volume has a strongly positive effect on the corn price change per percentage point increase in ethanol. This result is a bit of a numerical artifact that occurs because scenarios with low levels of baseline ethanol naturally lead to changes in production that are very large in percentage terms (causing a large denominator) even when they are moderate in volumetric terms.

The projection year is negatively associated with the normalized corn price results, indicating that price effects are expected to be more moderate farther into the future. This result is not surprising, particularly if the projection year reflects crop yields (which are typically assumed to improve over time)

[17] We reject the hypothesis that the coefficient on baseline corn ethanol production is equal to the negative of the coefficient on policy scenario corn ethanol production ($p = 0.03$).

and other types of technological progress that we were not able to include directly. The price change per billion gallons of corn ethanol is projected to decline by almost a percentage point over a ten-year period. Of course, if anticipated crop yields do not materialize due to climate change or other factors, then estimates of biofuel price effects in 2020 and beyond could turn out to be overly optimistic.

Accounting for ethanol co-products is another important technological factor in determining normalized corn price impacts. Studies that account for the use of a portion of corn ethanol feedstock as livestock feed find a significant reduction in corn price responsiveness.

Production of other international biofuels (largely sugarcane ethanol) does have a significant positive effect on normalized corn prices, as expected. However, inclusion of cellulosic biofuel and US and EU biodiesel expansion in the policy scenario has no significant effect on corn price impacts. Cellulosic feedstocks might have minimal impacts on food crop prices if they are grown on marginal lands, but it is surprising that biodiesel production—particularly based on US soy feedstock, which competes for farmland with corn—has no significant indirect effect on corn prices. Still, the international biofuel result confirms that it is inappropriate to attribute corn price changes solely to the change in corn ethanol production in scenarios that include other biofuels.

Specifying corn as the examined commodity rather than a more aggregate product such as cereals also increases estimated price effects, with a statistically significant effect in the first two equations. It is unsurprising that the effects of a corn ethanol mandate would be felt most strongly in corn markets themselves and be somewhat dissipated in other agricultural commodity markets. Finally, scenarios focusing on the RFS2 alone find lower absolute price changes but higher price change per billion gallons of corn ethanol.

It is worth re-emphasizing that we could not include all potential drivers of biofuel price effects in our meta-regression due to insufficient information. We conduct a sensitivity analysis to consider the effect of oil prices by re-running the meta-analysis including oil prices for those observations for which it is available (and setting this variable to zero otherwise) and a dummy variable indicating whether data on crude oil prices are missing. We found that oil prices had no significant effect on corn price effects in any of the three equations. This is not too surprising considering that the regressions already control for baseline and policy corn ethanol production.[18] Substitutability between biofuels and petroleum is also expected to be an important driver of corn ethanol production levels, but it is not clear if it would have much effect on corn prices after controlling for ethanol volumes. The elasticity of demand for corn is

[18] Oil prices have a significant negative effect on raw corn price changes if baseline and policy scenario corn ethanol levels are excluded, which makes sense because low oil prices will make biofuel mandates more likely to bind. These results are available from the authors upon request.

expected to play an important role, with inelastic demand leading to higher price effects, but we are unable to assess this factor due to lack of data.

Overall, our findings confirm the significance of several key factors identified in the literature in explaining seemingly disparate results across studies of the impact of biofuels on crop prices. Particularly important are differences in projected corn ethanol expansion volumes. Modeling framework, projection year, assumptions about ethanol co-products, inclusion of international biofuel increases, and use of corn as the studied commodity help explain much of the remaining variation across estimates. For analysts interested in understanding the effects of the increase in corn ethanol driven by the RFS2 mandate as the policy of interest, it would be appropriate to hold other types of biofuel production constant across the baseline and policy scenarios, to account for ethanol co-products, and to focus on corn as the commodity of interest; failure to do so could yield misleading estimates.

4. Short-run effects of U.S. ethanol expansion on corn prices

When agricultural markets are shocked exogenously by a change in policy or other factors such as drought or high oil prices, they typically do not instantaneously adjust to a new, long-run equilibrium. An examination of the adjustment process allows researchers to gain insight into the magnitude and duration of short-run impacts in response to the shock. How long this adjustment takes and the implications for prices depend on the ability of firms to modify production practices to accommodate this new information. When farmers have less flexibility in the near term, we expect larger increases in corn prices initially than occur in the long run.

To evaluate the short-run implications of demand or supply shocks, researchers must rely on different estimation techniques than typically used for evaluating long-run effects. Stochastic partial equilibrium models relax the assumption that individuals have perfect foresight. Farmers form expectations about the most likely realization of outcomes, but uncertainty in the market results in volatility; shocks or new information can increase this volatility. The effects of these shocks can be examined by simulating different scenarios and then comparing the results to a counterfactual. Another method that has been used to gain insight into the adjustment processes of markets to shocks is the structural variance autoregression approach. These models rely on time series data and include lags in

the model to allow for less-than-instantaneous adjustment to a new long-run equilibrium after an exogenous shock.[19]

Stochastic partial equilibrium approaches

We find five recent studies that empirically investigate the short run implications of ethanol expansion using stochastic partial equilibrium approaches. However, none of these studies has been published in a peer-reviewed journal. These studies explore a total of 26 scenarios (see Table 5). Because some studies focus on relaxing the mandate, while others examine the imposition of the mandate, we present the crop price changes in Table 5 in absolute terms.

With the exception of McPhail and Babcock (2008), all of the studies focus only on the implications of RFS2 for agricultural commodity prices. Three of the studies examine the implications of relaxing the mandate under various drought conditions. McPhail and Babcock (2008) examine the implications of the mandate under a variety of conditions related to gasoline price volatility, drought, and ethanol policy. Roberts and Tran (2012) use a competitive storage model to compare how markets would react to the mandate if they have several years to adjust to the new equilibrium versus a scenario in which the mandate is imposed instantaneously with no prior warning.[20]

As is the case with the long-run studies discussed previously, there is considerable variability across estimates of the short-run price effects resulting from a change in ethanol production. At the low end, McPhail and Babcock (2008) find almost no effect of relaxing the mandate under bumper crop conditions because it is largely non-binding. Scenarios that consider the relaxation or imposition of the mandate under drought conditions find corn price changes ranging from 8 to 28 percent.

On the high end, Roberts and Tran (2012) estimate short-run price effects ranging from 54 to almost 400 percent. This study differs from the others in a few key respects. As noted, it examines the effect of a sudden, unexpected imposition of an ethanol mandate. Second, price effects are largest when the demand elasticity for food is not allowed to adjust over time and the use of ethanol co-products to feed livestock are not included in the model. When consumers can reduce their caloric intake, change the types of foods they consume, or make up some portion of their calories via distiller's grains, price impacts are somewhat mitigated. Third, Roberts and Tran use a calorie-weighted average price of corn, rice, wheat and soy; the other studies examine the effect of the RFS on corn prices.[21] The

[19] See Almirall et al. (2012) for further explanation for how these models work.
[20] Roberts and Tran's long-run equilibrium results are discussed in the previous section.
[21] Note that Babcock (2012a) and (2012b) also report the effect of U.S. biofuel policy on soybean prices because of the biodiesel mandate within RFS2. We do not discuss these results in the paper.

authors expect that when grain storage is available and relatively inexpensive, the effect that unexpected demand shocks have on prices will be ameliorated over time by available inventories of grains. They find this to be the case, but when the full mandate is immediately binding, world food prices increase markedly in the first year before slowly declining to the new equilibrium long-run price.

Table 5. Studies Examining Short Run Impact of Corn Ethanol Expansion on Corn Prices

Study	Ethanol Scenarios	Policy Instrument	Conditions Examined	Absolute Crop Price Change
Babcock (2012a)	2	RFS2	Relaxing mandate; drought	15 - 20%
Babcock (2012b)	2	RFS2	Relaxing mandate; drought	20 - 26%
Roberts & Tran (2012)*	9	RFS2	Unexpected, sudden increase in mandate; co-products; demand & supply elasticities	54 - 390%
Tyner et al. (2012)	9	RFS2	Relaxing mandate; drought	8 - 28%
McPhail & Babcock (2008)	4	RFS2, tax credit	Mandate imposed, drought; bumper crop; no tax credit	0.2 - 25%

* Roberts and Tran (2012) use a calorie-weighted average price of corn, rice, wheat and soy (i.e., price of buying one year of calories for one person in 2010) instead of U.S. corn price.

As is true for the long-run studies discussed in section 3, another reason for the wide range of predicted price effects in the short run is that the ethanol production changes evaluated differ markedly across scenarios. For instance, Roberts and Tran consider an 11.1 billion gallon increase in ethanol production. Babcock (2012a) and Babcock (2012b) examine a complete waiver of a 13.6 billion gallon corn and advanced ethanol requirement as well as a partial waiver of 2.4 billion gallons (by allowing the use of carry-over RINs from previous years). Tyner et al. (2012) examine ethanol waivers of 2 billion, 3.4 billion, and 6.05 billion gallons. Finally, McPhail and Babcock (2008) consider the imposition of a 10 billion gallon ethanol mandate, which represents an increase in ethanol production relative to a baseline ranging from 0 (when there is a bumper crop) to almost 7 billion gallons (in the case of drought).
Table 6 normalizes the short-run price change results from the five stochastic partial equilibrium studies by expressing them in terms of the percent change in the corn price for every billion gallon increase in ethanol and the change in corn price per one percent increase in the quantity of ethanol. As previously mentioned, the studies vary with regard to whether they model the RFS2 as the reference or policy case. While the calculations are affected by whether the ethanol mandate is treated as the reference or policy case, these differences are generally small.

The change in corn price per billion gallon increase in ethanol ranges from about 3.5 percent to almost 37 percent, while the change in price per one percent increase in ethanol ranges from 0.1 percent to 2 percent. Taking the study-weighted average across all scenarios, each billion gallon increase in corn ethanol raises corn prices by 9.74 percent in the short run. Similarly, a 10 percent increase in corn ethanol production increases corn prices by an average of 10.1 percent. As expected, the short-run effects on corn price are substantially higher than those from the long-run studies summarized in Table 3. (Recall that long run study-weighted average price per billion gallons is about 2.8 percent, while the average price per 10 percent increase is about 2.4 percent.)

Table 6. Short-Run Impact of Corn Ethanol Expansion on Absolute and Normalized Corn Prices

Study	Absolute crop price change	Price change per billion gallon change in ethanol	Price change per 1% change in ethanol
Babcock (2012a)	15-20%	10.3 - 10.7%	1.5%
Babcock (2012b)	20-26%	14.2 - 15.1%	1.9 - 2.0%
Roberts & Tran (2012)*	54-190%	4.9 - 35.0%	0.2 - 1.4%
Tyner et al. (2012)	8-28%	3.7 - 4.6% **	0.5 - 0.7% **
McPhail & Babcock (2008)	0.2-25%	3.5 - 8.0%	0.1 - 0.9%
Study-weighted average	44.8%	9.74%	1.01%

* Roberts and Tran (2012) use a calorie-weighted average price of corn, rice, wheat and soy (i.e., price of buying one year of calories for one person in 2010) instead of U.S. corn price.
**Relaxing the mandate by 2 BG had no effect on 2012-2013 ethanol production in two scenarios, so it was not possible to calculate elasticities in these cases.

While variability within a study is generally much smaller when price changes are normalized by ethanol production changes, Roberts and Tran (2012) have semi-elasticities that range from 4.9 percent to 36.7 percent and elasticities that range from 0.2 percent to 1.4 percent. This reflects the large number of sensitivity analyses included in the study (i.e., the inclusion of co-products and changes in the elasticities of supply and demand).

There also continues to be a certain amount of variability across studies. Table 7 shows that the models differ in their treatment of co-products, inclusion of the oil market, and how the commodity is defined. As expected, given the near-term focus of the studies, the range of baseline and policy ethanol scenarios considered is much narrower than in the long run studies. One of the largest sources of variation across and (in some cases, within) studies is in the baseline yield assumption. This is due, in part, to the fact that the objective of three of the studies is to examine how drought conditions combined with ethanol policy affect corn prices. Yield is also a key source of stochasticity in many of the

models. For instance, stochasticity in the Babcock (2012a, 2012b) studies originates from uncertainty regarding corn and soybean yields and demand for ethanol in the U.S. (which is determined by the quantity of ethanol available and gasoline prices). Babcock (2012a) estimates impacts assuming corn yields are well below average due to drought and that there is a low buffer stock (i.e., accumulated inventory) of corn. Babcock (2012b) leaves all assumptions and scenarios unchanged from Babcock (2012a) except for assuming far lower crop yields and harvested acres for corn and soybeans.

Table 7. Key Variations across Short-Run Ethanol Studies

	Mean*	Std. dev.	Min	Max	Obs
Baseline corn ethanol (bgal)	10.64	4.68	3.9	14.3	26
Policy scenario corn ethanol (bgal)	12.15	2.46	7.95	15	26
Ethanol co-products included (1 = yes, 0 = no)	67%	0.47	0	1	13
Year	2012	2.49	2008	2015	26
Baseline yield (bushels/acre)**	131.88	9.72	113	169	26
Oil prices ($)	87.23	23.97	40	121	15
Corn (vs. aggregate commodity) (1 = yes, 0 = no)	75%	0.45	0	1	26
RFS2 policy scenario (1 = yes, 0 = no)	100%	0	--	1	26

*Each study is given equal weight when calculating the mean and standard deviation to avoid giving more weight to studies with a greater number of scenarios.

** Yield per acre for Roberts and Tran (2012) is back-calculated from the information available in the paper.

Tyner et al. (2012) also examine how an ethanol waiver might affect corn prices under a variety of drought conditions (referred to as severe, median, and weak).[22] Tyner et al.'s weak drought conditions correspond most closely to the yield assumptions in Babcock (2012a), while Tyner et al.'s median and severe drought conditions fall on either side of the yield assumption made in Babcock (2012b). The findings of Tyner et al. (2012) echo those of Babcock (2012a, 2012b), but are noticeably smaller, even after normalizing by ethanol production. Tyner et al. point to greater short-run responsiveness of ethanol demand to new information in their model as one source of these differences. In particular, they state that Babcock's model only allows limited flexibility in how blenders and refiners respond to shocks. Thus, while relaxing the mandate slightly—to about 10 billion gallons—may garner some response, further reductions do not.

McPhail and Babcock (2008) have the highest and lowest yield assumptions across all five studies, to capture severe drought and bumper crop conditions. Corn supply stochasticity in their model

[22] Tyner et al. (2012) note that the effect of a waiver of the mandate in alleviating corn price increases will be very small or zero if farmers and refiners have limited flexibility to adjust production practices in the short run, in particular if the market is not able to move away from a 10 percent blend of ethanol in fuel.

is also based on uncertainty in planted acres and corn yields, while stochasticity in corn demand is based on uncertainty about export demand, gasoline prices, and corn ethanol capacity in the U.S.[23]

Back calculating the corn yield in bushels per acre from Roberts and Tran (2012) indicates that their mean yield assumption is roughly equivalent to Tyner et al.'s (2012) weak drought condition. Roberts and Tran (2012) use a stochastic dynamic programming competitive storage model that is solved recursively for the corn, soybean, rice, and wheat markets. Demand and supply of grains are separately identifiable since harvest and cultivated land decisions are a function of expected (and therefore, uncertain) future prices and yields, while demand is a function of current price. Interaction with oil markets is not considered in their model.

Structural vector autoregression approaches

Macro-econometric time-series approaches such as structural variance autoregression also have been used to examine short run agricultural market responses to ethanol shocks. However, these approaches do not yield enough information to calculate price effects per unit of ethanol production. Instead, these models are typically used to answer two types of questions: what proportion of the variance in the error term comes from a specific shock to the system (referred to as forecast error variance decomposition), and how does the shock affect the variables of interest over time (referred to as tracing out the impulse response function)?[24]

Zhang et al. (2009b) examine how much ethanol policies have contributed to short-run price spikes for corn using econometric techniques that capture interactions across markets over time. They find that ethanol prices in 2000-2007 do not explain any of the variation in prices for corn in the short run. Impulse response functions demonstrate that one reason for this is that a shock to corn prices does not persist: corn prices return to their long-run equilibrium value within ten weeks of an ethanol price shock. Qiu et al. (2011) find that exogenous shocks in the demand for ethanol between 1994 and 2010 explain about 4 percent of the variation in corn prices in the short run. Unlike Zhang et al. (2009), this small effect persists over many months in their model. Gardebroek and Hernandez (2012) find evidence

[23] McPhail and Babcock (2008) also report the coefficients of variation with respect to corn and gasoline prices. Results demonstrate that elimination of the mandate reduces corn price variability. In a case where there is a negative shock to corn yields (i.e., a drought), corn prices increase by less than they would have with an ethanol mandate. Oil prices also matter: when oil prices are low, it is more likely that the mandate is binding, so that its elimination would have a greater effect on corn prices.

[24] Zhang et al. (2009b) also examine the strength and direction of ethanol, corn, and gasoline prices using co-integration methods and Granger causality tests. They find no evidence of a long-run relationship (i.e., co-integration) between corn and ethanol prices.

that energy and corn markets have become more inter-related: returns on corn and ethanol are more strongly correlated after ethanol replaced MTBE as an oxygenate in gasoline in 2006. However, they do not find evidence that shocks in ethanol prices affect corn prices (i.e., they find no mean or volatility spillovers from ethanol to corn markets via price).[25]

These results contrast with other time series-based studies that find a stronger association between ethanol and corn prices. Almirall et al. (2012) find about 30 percent of the corn price rise from 2006 to 2007 was due to expanded ethanol production. Using an impulse response function, they also examine the effect of taking 1 million acres of corn out of food production (i.e., it is instead used to produce ethanol). They find that it is associated with a 4 cent per bushel increase in the price of corn in the first year, but that this effect does not persist.[26] When there are repeated negative shocks to corn acreage (for instance, from a continued buildup of ethanol production), Almirall et al. (2012) show a continued increase in corn prices from 4 cents per bushel to a peak of 10 cents per bushel in years two and three. Carter et al. (2012) also find that corn prices would have been 30 percent lower for the 2006-2010 period if ethanol production had been kept at 2005 levels (i.e., absent inventory supply or demand shocks over this time period). However, it is important to note that neither of these studies separate out the effect of ethanol policy from market-driven effects.

Zilberman et al. (2012) note that the directional relationship between ethanol prices and food prices is theoretically ambiguous, making it unsurprising that this strand of literature has found mixed results. They argue that it is necessary to examine the relationship between biofuel production (rather than prices) and food prices to identify the effects of biofuel policies on commodity markets.[27]

4. Ethanol Production and Global Food Security

Higher agricultural commodity prices due to increased ethanol production are of particular concern in developing countries. First, the majority of developing countries are net importers of food, which means that they often face world prices for agricultural commodities (Valdes 2012). Second, the world's poor are disproportionately affected by higher commodity prices due to their inelastic demand for agricultural staples. Populations in developing countries rely heavily on raw agricultural products and

[25] Unlike Zhang et al. (2009), Gardebroek and Hernandez (2012) find that volatility observed in the ethanol market is related to past volatility in the corn market.

[26] To compare this result to those from stochastic partial equilibrium models, we would need to know what a loss in acreage means for corn production. We cannot calculate this unless we impose assumptions about corn yield.

[27] A series of papers by Lagi et. al (2011, 2012) examine various explanations for recent food price increases. They find that increased ethanol production is consistent with gradually increasing food prices since 2004 while speculative behavior appears to explain the peaks in 2007/08 and 2010/2011.

spend a far greater portion of their income on staple food expenditures relative to consumers in the developed world (Roberts and Schlenker 2013; Zhang et al. 2009a; Runge and Senauer 2007).[28] As a result, even a relatively small increase in agricultural prices has potentially dramatic implications for consumers in these countries (Chakravorty et al. 2012). Poor households are likely to respond to increases in food prices by reducing food consumption, which may lead to caloric and nutritional deficiencies; and by spending less of their income on other goods and services, such as education, savings, and investment. It is important to note that offsetting positive effects can occur for farmers in these countries, who are expected to benefit from higher prices by earning additional income if they are net food producers (Swinnen and Squicciarini 2012).

Food security is a real issue for large numbers of people, absent consideration of increased ethanol production. The FAO (2011b) estimates that about 850 million people in developing countries – about 16 percent of the total population in these countries – were undernourished in 2007-2009, with Asia and Sub-Saharan Africa making up the majority. Overall, the number of undernourished has remained essentially unchanged for 2011-2012, though this masks sizable regional shifts (i.e., 20 percent decline in Asia; 38 percent increase in Sub-Saharan Africa) that the FAO attributes to the varying ability of countries to limit or mitigate the effects of food price shocks that occurred in 2006-2008.

Future biofuel expansion has the potential to exacerbate this situation. It can contribute to commodity price volatility, which increases uncertainty regarding food availability (McPhail and Babcock 2012). Future food consumption trends in developing countries are particularly dependent upon how much corn is diverted to non-food uses.[29] Loss of agricultural productivity due to climate change also affects yield trends and may make it harder to meet food and fuel objectives (NRC 2012), while biofuel production can further exacerbate food price volatility due to climate change (Diffenbaugh et al. 2012).

While many studies have estimated the commodity price effects of biofuel expansion, fewer researchers have examined the implications of biofuels for food security in developing counties by translating commodity price hikes into changes in the number of people in poverty or suffering from hunger.[30] That said, most experts agree that short run effects of biofuel expansion on food security are

[28] The poorest quintile of most developing countries spend well over 50 percent of their income on food, with some spending greater than 70 percent on food expenditures (FAO 2011a).

[29] Demand-side shifts, such as changes in consumption and dietary preferences also generate unpredictable effects in global markets. Population and income growth in the major developing countries have the potential to induce large increases in the demand for food, energy, and land. Roberts and Schlenker (2013) point out that China's population has doubled over the past 50 years, but aggregate meat consumption has increased by 33 times in the same amount of time.

[30] There is a large qualitative literature in this area, however. See Timilsina et al. (2012).

more severe than long run effects; in the long run adjustments in land conversion and improvements in technology will likely mitigate some effects (Chakravorty 2012). There is also an existing literature estimating the short- and long-run poverty implications of food price increases generally (i.e., not resulting from biofuel production *per se*). For instance, a recent World Bank report (Ivanic et al. 2011) indicates that short-run impacts can vary widely by country, depending on the degree to which global prices are transmitted into the local market and differences in the ways that households consume and produce goods across countries. Even accounting for these differences, they estimate that, on net, food price increases in the last half of 2010 raised the number of people living in extreme poverty (accounting for countries where poverty is estimated to decline because they are net sellers of food) by 43.7 million.[31]

Three of the studies covered in Section 3 empirically estimate the long-run impacts of ethanol expansion on global or regional food security (Rosegrant et al. 2008; Roberts and Schlenker 2013; Huang et al. 2012). We also identified four additional studies that examine the impact of biofuels expansion on food security but were excluded from section 3 because they do not report estimates of the change in corn prices or US corn ethanol production (Fischer et al. 2009, Bryant et al. 2010, Timilsina et al. 2012, Chakravorty et al. 2012b). As shown in Table 8, some of these studies take a broad global approach, while others focus on specific low- or middle-income countries. The seven papers summarized in Table 8 also differ in their use of partial equilibrium or multi-market models representing the agriculture and biofuel sectors, versus pairing these types of detailed models with a general equilibrium approach.

Table 8: Studies Estimating Impact of Ethanol Expansion on Food Security

Study	Model	Countries/ regions	Policy scenarios	Crop price change *
Rosegrant et al. (2008)	PE agricultural model	115	RFS2, EU, and Brazil biofuel policy; doubling existing targets	26% - 72%
Fischer et al. (2009)	GE model + PE agricultural model	34	2008 global biofuel policy; doubling of existing targets	8%-35%
Bryant et al. (2010)	Static GE model	9	RFS2	-
Timilsina et al. (2012)	Dynamic CGE model + PE land and biofuel sector models	112	Announced global biofuel policies; doubling of those targets	1%– 3.7%
Roberts & Schlenker (2013)	Supply and demand model		RFS2	20% - 30%

[31] Ivanic et al. (2011) include a wide range of commodity price increases in their study. Global maize prices increased by about 73 percent over this time frame. Likewise, global sugar prices increased by 76 percent, while edible oil prices increased by 54 percent. Global rice prices increased by 17 percent from June to December 2010.

Chakravorty et al. (2012b)	Dynamic multi-market model	India	RFS2 and Indian biofuel mandates	12%
Huang et al. (2012)	CGE model + PE ag. model	China	RFS2, EU, , and Brazil biofuel policy; market-driven expansion	15% - 50%

* Fischer et al. (2009) report changes in cereal prices out to 2050. They do not report changes in corn production or prices separately. For comparability to results from other models, we report the effects in 2020. Roberts and Schlenker (2013) use a calorie-weighted average of corn, soy, rice, and wheat. Timilsina et al. (2012) only report price and quantity effect in terms of percent change and do not isolate the effects of corn ethanol production. Bryant et al. (2010) do not report change in crop prices.

Most of the studies examine the combined effect of ethanol expansion policies from the United States and other world regions on food security, the exception being Roberts and Schlenker (2013) and Bryant et al. (2010), who examine the impact of U.S. policy only. Rosegrant et al. (2008) compare a 2020 world where biofuel policies in the U.S., Europe, and Brazil are maintained at 2010 levels to moderate biofuel expansion based on already announced plans, and more drastic expansion where demand is an additional 50 percent higher in 2010 and 100 percent higher in 2015 and 2020. Similarly, Timilsina et al. (2012) examine the implementation of announced biofuel policies in more than 18 countries, and a doubling of announced targets within the same timeframe.[32] Fischer et al. (2009) examine the impacts of global biofuel expansion using first-generation biofuels on food security out to 2050 based on current biofuel policy only (as of 2008), and on a doubling of the amount in the first scenario.[33] Huang et al. (2012) evaluate biofuel expansion scenarios in which only market forces drive further biofuel expansion, and where U.S., EU, and Brazilian ethanol mandates for 2020 are binding, focusing on impacts in China. Chakravorty et al. (2012b) examine the impact of US and Indian biofuel mandates on household welfare and poverty in India. Roberts and Schlenker (2013) and Bryant et al. (2010) both examine the reduction in calories available for food consumption worldwide when RFS2 is in place.

Changes in crop prices reported in Table 8 are for 2020 in most cases (Chakravorty et al. and Roberts and Schlenker report impacts in 2015). The absolute crop price changes reflected in these studies are consistent with the larger body of long-run estimates discussed in section 3: they range from 1 percent (Timilsina et al.) to 72 percent (Rosegrant et al.). Fischer et al. (2009) find that cereal prices increase by about 10 percent in 2020 relative to the baseline under the more moderate biofuel expansion scenario. In the more aggressive biofuel expansion scenario, cereal prices increase by about

[32] Timilsina et al. (2012) note that there are significant food price effects in the baseline. For instance, existing biofuel policies coupled with substantial oil price increases in the baseline result in corn prices increasing 31 percent by 2020. As expected processed food prices see little effect since agricultural products represent a relatively small share of its cost.

[33] Sensitivity analyses also are carried out to examine the role of technology–specifically the availability of second-generation fuels. We focus on the year 2020 to make findings more readily comparable to other studies.

30 percent in 2020 if slower deployment of second-generation fuels is assumed; optimistic assumptions regarding availability lead to lower price impacts. Roberts and Schlenker find that ethanol expansion reduces world caloric production of these commodities for other uses by about 5 percent and results in about a 20-30 percent increase in the calorie-weighted price, depending on assumptions about ethanol co-products. Huang et al. (2012) find world corn price increases ranging from 15 to 50 percent but that only about a quarter of this is passed through to the Chinese market. Chakravorty et al. (2012) find that biofuel policies result in world price increases of 7 percent for rice, 12 percent for wheat, less than one percent or sugar, and 12 percent for "other crops" (including other cereals, starches, and oil) in 2015; the effects on prices in India depend on the degree of pass-through.

When translated into change in corn price per billion gallon increase in ethanol (see Table 9), the range across these studies is narrower than what is represented in Section 3: 0.3 to 2.6 percent (as opposed to -0.3 to 8.7 percent). Note that the price change per billion gallon measure presented in Table 9 is also slightly different from the results shown in section 3 for some studies because there we focused exclusively on US corn ethanol production. In particular, we have included global biofuel production from all feedstocks in the denominator for the Fischer et al. (2009) and Timilsina et al. (2012) studies because they do not break out biofuel production by country and feedstock. We also include both the corn and cellulosic biofuel production reported in Bryant et al. (2010).

Table 9: Implications of Ethanol Expansion for Food Security

Study	Crop price change*	Price change per billion gallon increase in ethanol	Absolute additional people at risk of hunger (millions)	Additional people at risk of hunger (millions) per billion gallon increase in ethanol
Rosegrant et al.*	26% - 72%	2.2% - 2.6%	4.4-9.6	0.39 - 0.43
Fischer et al.**	8%-35%	0.3%-0.6%	40-140	1.4 - 2.5
Bryant et al.**	-	-	0.8-1.2	0.2 - 0.24
Timilsina et al.**	1% - 3.7%	-	-	-
Roberts & Schlenker *	20% - 30%	1.8% - 2.7%	132	12
Chakravorty et al.	12%	2%	16-42	2.7-7
Huang et al.	15% - 50%	1.4% - 1.5%	-	-

* Rosegrant et al. (2008) only report food security impacts on preschool age children.
** Timilsina et al. (2012) only report price and quantity effect in terms of percent change and do not isolate the effects of corn ethanol production. Fischer et al. (2009) report percent change in cereal prices but do not separate out the change in corn price. Bryant et al. (2010) do not report changes in corn prices.
***Chakravorty et al. (2012) do not report baseline ethanol production in their paper. From the information available, we have assumed it is 6 billion gallons absent additional ethanol policy in the U.S. and India. They also focus on poverty rather than hunger.

Food security impacts implied by each of the studies of ethanol expansion are often reported in terms of the increase in the number of people who will be at risk of hunger (i.e., are below minimum caloric requirements) or will fall into extreme poverty (i. e., living on less than $1.25 per day). While we cannot express these numbers in percentage terms – few of these studies report the risk of hunger in the baseline – we can express the results from a few of the papers in terms of a common denominator (i.e., per billion gallons in ethanol production) to make them more readily comparable (see Table 9). Note, however, that even when this is possible there are important differences across studies that influence the estimated number of people who will be at risk of hunger or fall into poverty. For instance, Chakravorty et al. (2012) only examine impacts in India. After accounting for changes in consumption in response to higher domestic prices and rising agricultural wages and incomes, Chakravorty et al. (2012) find that an additional 16 - 42 million people in India may be forced into poverty. The higher estimate is predicated on full pass-through of world prices into the domestic market, while the lower estimate assumes some government intervention to prevent full pass-through. Likewise, Rosegrant et. al (2008) only include the number of pre-school age children at risk of hunger, not the population as a whole. They find that increased ethanol expansion results in significantly reduced calorie availability and heightened levels of regional malnourishment in 2020, with particularly large effects occurring in sub-Saharan Africa (4 and 8 percent, respectively, under moderate and drastic biofuels expansion), a region already suffering from food scarcity.

Bryant et al. (2010) do not restrict themselves to a sub-sample of the population. They predict moderate effects on the number of people at risk of hunger, similar in magnitude to Rosengrant et al. (2008) when expressed per billion gallon of ethanol. This moderate effect may be due to the relatively small increase in ethanol production that is modeled (5 billion gallons). However, the authors do not directly report the change in corn or food prices from their model, so a comparison to the price effects of other studies is not possible. It may also be due to the assumption that corn stover is available as a feedstock to produce cellulosic ethanol.[34] While the predicted effect of ethanol expansion on hunger is relatively small, it is concentrated in a few regions; more than 40 percent of those at risk of hunger are located in China and the Far East. The estimated effect also falls as the cost of producing cellulosic biofuels decreases.

[34] Cellulosic is available under two scenarios: (1) at today's full cost; and (2) at 55 percent of the full cost. In the first case, 1.25 billon of the 5 billion gallons of total ethanol produced is met by cellulosic from corn stover. In the second case, 4 billion gallons of the requirement are met this way. It is not possible to separate out the effect of corn from cellulosic ethanol on the number of people at risk of hunger.

Fisher et al. (2009) find that 40 million to 140 million more people will be at risk of hunger in 2020 than in the baseline. This translates to between 1.4 million and 2.5 million people per billion gallons of ethanol. While about two-thirds of the cereals needed to produce more ethanol stem from expanded crop production in their model –largely in developed countries –the remaining third derives from reduced consumption for food and feed – largely in developing countries. Similar to the Bryant et al. result, wide availability of second-generation fuels beyond 2020 substantially reduces the number of people at risk of hunger under the aggressive biofuel expansion scenario (from 140 million to 80 million). South Asia accounts for the vast majority (75- 90 percent) of the increase in those at risk of hunger worldwide.

At the high end, Roberts and Schlenker (2013) find that higher prices negatively affect consumers but positively affect producers. Developing countries that are largely net food importers are negatively impacted: The authors do a back of the envelope calculation that the estimated reduction in food consumption is equivalent to the caloric requirements to feed about 132 million people. However, because this is not a modeled result, it does not account for the ability of individuals to substitute to cheaper foodstuffs: it assumes they will adapt to higher prices only by eating less.

We are not able to express the food security implications of two of the studies in terms of the number of people put at risk of hunger or falling into poverty. However, their results are worth mentioning. Timilsina et al. (2012) find that , even for the relatively moderate price increases experienced in the announced target scenario, impacts on food supply are significant in some developing countries such as India (0.5 percent reduction in food supply) and sub-Saharan Africa (0.2 percent reduction). Huang et al. (2012) find that production and exports of feedstock crops grown in China increase due to higher prices, but production of many other crops decline. As a result, farmers in China tend benefit from biofuel expansion, with relatively more of this benefit accruing to poorer farmers because the share of their income from agriculture is higher. Huang et al. (2012) do not estimate the effect of biofuel expansion on Chinese consumers, but expect they are negatively affected since they experience higher commodity prices without an offsetting increase in income.

5. Conclusions

Economic theory suggests that diverting a sizable share of corn production to fuel ethanol will put upward pressure on corn prices. While several empirical analyses confirm this finding, the literature has reported price effects from biofuel expansion ranging from nil to over 70 percent. We scrutinize these

divergent results to determine whether they are more comparable once we control for the quantity of ethanol production and other scenario differences and assumptions.

Our review of long-run analyses released between 2008 and 2012 shows that the study-weighted average effect of an additional billion gallons of corn ethanol on corn prices is approximately 2 to 3 percent. A meta-analysis finds that modeling framework, baseline and policy scenario ethanol production, inclusion of ethanol co-products, projection year, and international biofuel production explain much of the divergence among estimates. Due to sparse data about the elasticity of substitution between biofuels and petroleum fuels, as well as elasticities of crop supply and demand, we were unable to assess whether these factors might help explain the remaining variation in estimates. We urge authors to report these and other key assumptions in future analyses of biofuel impacts to foster transparency and comparability among studies.

We also examine recent literature highlighting the short-run price impacts of ethanol production. The findings confirm that a temporary waiver of biofuel targets due to drought conditions is expected to have a larger effect on corn prices than a long-term policy shift in which markets have time to adjust. In this case, each billion gallon increase in corn ethanol is expected to raise corn prices by 5 to 10 percent.

A limited number of studies also relate crop price increases caused by biofuel production to food security and poverty in developing countries. Farmers in these countries who are net food sellers could see a boost in their incomes, but on balance biofuel policies are expected to increase the numbers of people at risk of hunger and poverty. While short-run price swings due to weather or unanticipated policy shocks seem particularly relevant for low-income consumers in developing countries, the food security studies included in our review are all based on long-run economic models. A direction for future research might be to combine analysis of short-run price impacts with modeling that projects numbers of people at risk of hunger to gain a fuller picture of potential food security impacts associated with biofuel policies.

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Appendix

Table A. List of Variables from 18 Long-Run Ethanol Studies

Study	Model	Modeling framework	Policy scenario	RFS2	Commodity	Projection year	Ethanol co-product included
Anderson & Coble	Probabilistic supply and demand model	PE	RFS2	1	corn	2008	no
Bento et al.	Multi-market model	PE	RFS2, VEETC continues	1	corn	2012	yes
		PE	RFS2, VEETC discontinued	0	corn	2012	yes
		PE	RFS2, VEETC continues	1	corn	2015	yes
		PE	RFS2, VEETC discontinued	0	corn	2015	yes
Chakravorty et al.	Multi-market model	PE	RFS2, EU, middle-income country biofuel policy	0	cereals	2022	yes
Chen and Khanna	BEPAM	PE	RFS2	1	corn	2022	yes
		PE	RFS2, tax credits	0	corn	2022	yes
		PE	RFS2, tax credits, tariffs	0	corn	2022	yes
		PE	RFS2; lower-cost sugarcane ethanol	1	corn	2022	yes
		PE	RFS2, tax credits; lower-cost sugarcane ethanol	0	corn	2022	yes
		PE	RFS2, tax credits, tariffs; lower-cost sugarcane ethanol	0	corn	2022	yes
Cui et al.	Multi-market model	PE	no ethanol policy	0	corn	2009	yes
		PE	status quo (RFS2)	1	corn	2009	yes
		PE	first-best policy	0	corn	2009	yes
		PE	optimal fuel tax and biofuel subsidy	0	corn	2009	yes
		PE	optimal biofuel subsidy	0	corn	2009	yes
		PE	optimal mandate	0	corn	2009	yes
Fernandez-Cornejo et al.	FARM II	GE	RFS2 & Brazilian ethanol policy, expected yield increases	0	corn	2015	no
		GE	RFS2 & Brazilian ethanol policy, additional yield increases	0	corn	2015	no
Gehlhar et al.	USAGE	GE	RFS2, tax credits retained	1	corn	2022	yes

Study	Model	Modeling framework	Policy scenario	RFS2	Commodity	Projection year	Ethanol co-product included
		GE	RFS2, tax credits retained	1	corn	2022	yes
		GE	RFS2, tax credits halved	1	corn	2022	yes
		GE	RFS2, tax credits halved	1	corn	2022	yes
		GE	RFS2, tax credits eliminated	1	corn	2022	yes
		GE	RFS2, tax credits eliminated	1	corn	2022	yes
Hayes et al.	FAPRI	PE	RFS2, tax credits, and import tariffs	0	corn	2022	yes
		PE	Biofuel tax credits	0	corn	2022	yes
Hertel et al.	GTAP-BIO	GE	RFS2	1	CG*	2007	yes
		GE	RFS2 with fixed food consumption	1	CG	2007	yes
Huang et al.	CAPSiM-GTAP	GE	Market-driven expansion	0	corn	2020	yes
		GE	RFS2, EU, and Brazilian biofuel policy	0	corn	2020	yes
Mosnier et al.	GLOBIOM	PE	50% of RFS2	0	corn	2010	yes
		PE	75% of RFS2	0	corn	2010	yes
		PE	125% of RFS2	0	corn	2010	yes
		PE	150% of RFS2	0	corn	2010	yes
		PE	50% of RFS2	0	corn	2020	yes
		PE	75% of RFS2	0	corn	2020	yes
		PE	125% of RFS2	0	corn	2020	yes
		PE	150% of RFS2	0	corn	2020	yes
		PE	“high corn” expansion of RFS2	0	corn	2020	yes
		PE	50% of RFS2	0	corn	2030	yes
		PE	75% of RFS2	0	corn	2030	yes
		PE	125% of RFS2	0	corn	2030	yes
		PE	150% of RFS2	0	corn	2030	yes
		PE	“high corn” expansion of RFS2	0	corn	2030	yes
OECD-FAO	AGLINK-COSIMO	PE	RFS2 and EU biofuel policy	0	CG	2015**	yes
		PE	Removal of all policy support	0	CG	2015	yes

Study	Model	Modeling framework	Policy scenario	RFS2	Commodity	Projection year	Ethanol co-product included
Roberts & Schlenker	Supply and demand model	PE	RFS2	1	CSRW	2009	no
		PE	RFS2	1	CSRW	2009	yes
Roberts & Tran	Competitive storage model	PE	RFS2	1	CSRW	2015	no
		PE	RFS2, demand less elastic	1	CSRW	2015	no
		PE	RFS2, demand more elastic	1	CSRW	2015	no
		PE	RFS2	1	CSRW	2015	yes
		PE	RFS2 demand less elastic	1	CSRW	2015	yes
		PE	RFS2 demand more elastic	1	CSRW	2015	yes
		PE	RFS2, alternative elasticities	1	CSRW	2015	no
		PE	RFS2, alternative elasticities, demand less elastic	1	CSRW	2015	no
		PE	RFS2, alternative elasticities, demand more elastic	1	CSRW	2015	no
Rosegrant et al.	IMPACT	PE	RFS2, EU, and Brazilian biofuel policy	0	corn	2020	no
		PE	Doubling RFS2, EU, and Brazilian biofuel targets	0	corn	2020	no
Thompson et al.	FAPRI-MU	PE	RFS2	1	corn	2014	yes
Tyner et al.	Partial equilibrium model	PE	RFS2	1	corn	2006	yes
		PE	RFS2	1	corn	2006	yes
		PE	RFS2	1	corn	2006	yes
		PE	RFS2	1	corn	2006	yes
		PE	fixed subsidy	1	corn	2006	yes
		PE	fixed subsidy	1	corn	2006	yes
		PE	fixed subsidy	1	corn	2006	yes
		PE	fixed subsidy	1	corn	2006	yes
		PE	fixed subsidy	1	corn	2006	yes
		PE	fixed subsidy	1	corn	2006	yes
		PE	fixed subsidy	1	corn	2006	yes

Study	Model	Modeling framework	Policy scenario	RFS2	Commodity	Projection year	Ethanol co-product included
		PE	variable subsidy	1	corn	2006	yes
		PE	variable subsidy	1	corn	2006	yes
		PE	variable subsidy	1	corn	2006	yes
U.S. EPA	FAPRI	PE	RFS2	1	corn	2022	yes
U.S. EPA	FASOM	PE	RFS2	1	corn	2022	yes

*CG: coarse grains; CSRW: calorie-weighted average of corn, soy, rice, and wheat

**: OECD-FAO reports results for a 2013-2017 average; we use 2015 in the analysis.

Table A. List of Variables from 18 Long-Run Ethanol Studies (continued)

Study	Baseline corn ethanol (bgal)	Policy scenario corn ethanol (bgal)	Cellulosic ethanol increase (bgal)	US biodiesel increase (bgal)	EU biodiesel increase (bgal)	Other international biofuel increase (bgal)	Baseline oil price ($/bbl)
Anderson & Coble	8.53	9.5	0	0	0	0	
Bento et al.	11.6	13.2	0	0	0	0	69
	11.6	13.1	0	0	0	0	69
	12.0	15.0	0	0	0	0	78
	12.0	15.0	0	0	0	0	78
Chakravorty et al.	7.0	15.0	21	0	1.4	2.1	121
Chen and Khanna	3.9	11.5	23	0	0	1.3	
	3.9	15.0	19	0	0	1.6	
	3.9	15.0	19	0	0	1.3	
	3.9	10.0	19	0	0	8.3	
	3.9	12.3	16	0	0	8.9	
	3.9	13.9	16	0	0	6.6	
Cui et al.	6	0	0	0	0	0	63
	6	11	0	0	0	0	63
	6	14	0	0	0	0	63
	6	16	0	0	0	0	63
	6	16	0	0	0	0	63
	6	17	0	0	0	0	63
Fernandez-Cornejo et al.	4.7	15.0	0	0	0	5.3	
	4.7	15.0	0	0	0	5.3	
Gehlhar et al.	8.0	15.0	16	0	0	0	80
	8.0	15.0	16	0	0	0	101
	8.0	15.0	16	0	0	0	80
	8.0	15.0	16	0	0	0	101
	8.0	15.0	16	0	0	0	80
	8.0	15.0	16	0	0	0	101

Study	Baseline corn ethanol (bgal)	Policy scenario corn ethanol (bgal)	Cellulosic ethanol increase (bgal)	US biodiesel increase (bgal)	EU biodiesel increase (bgal)	Other international biofuel increase (bgal)	Baseline oil price ($/bbl)
Hayes et al.	9.2	16.9	16	0	0	0	75
	16.6	25.5	16	0	0	0	105
Hertel et al.	1.8	15.0	0	0	0	0	
	1.8	15.0	0	0	0	0	
Huang et al.	4.9	40.0	0	0.9	7.0	13	60
	4.9	15.0	0	0.9	6.0	8.7	60
Mosnier et al.	13.4	6.7	0.2	-0.325	0	-6.43028	
	13.4	10.0	0.3	-0.1625	0	-3.21514	
	13.4	16.7	0.5	0.1625	0	3.215142	
	13.4	20.1	0.7	0.325	0	6.430284	
	15.0	7.5	7	-0.5	0	-1.665	
	15.0	11.3	10	-0.25	0	-0.8325	
	15.0	18.8	17	0.25	0	0.8325	
	15.0	22.5	21	0.5	0	1.665	
	15.0	21.3	7	0	0	0	
	15.0	7.5	7	-0.5	0	-1.665	
	15.0	11.3	10	-0.25	0	-0.8325	
	15.0	18.8	17	0.25	0	-2.08	
	15.0	22.5	21	0.5	0	1.665	
	15.0	21.3	7	0	0	0	
OECD-FAO	12.0	15.0	1.3	1.9	2.0	1.0	104
OECD-FAO	12.0	10.6	0	-0.4	-2.8	-2.0	104
Roberts & Schlenker	0.0	11.0	0	0	0	0	
	0.0	11.0	0	0	0	0	
Roberts & Tran	3.9	15.0	0	0	0	0	
	3.9	15.0	0	0	0	0	
	3.9	15.0	0	0	0	0	

Study	Baseline corn ethanol (bgal)	Policy scenario corn ethanol (bgal)	Cellulosic ethanol increase (bgal)	US biodiesel increase (bgal)	EU biodiesel increase (bgal)	Other international biofuel increase (bgal)	Baseline oil price ($/bbl)
	3.9	15.0	0	0	0	0	
	3.9	15.0	0	0	0	0	
	3.9	15.0	0	0	0	0	
	3.9	15.0	0	0	0	0	
	3.9	15.0	0	0	0	0	
	3.9	15.0	0	0	0	0	
Rosegrant et al.	3.8	14.2	0	>0	>0	>0	
	3.8	28.4	0	>0	>0	>0	
Thompson et al.	13.0	17.7	0	0	0	0	
Tyner et al.	0.0	15.0	0	0	0	0	40
	1.0	15.0	0	0	0	0	60
	8.0	15.0	0	0	0	0	80
	13.0	15.0	0	0	0	0	100
	0.0	1.9	0	0	0	0	40
	1.2	10.7	0	0	0	0	60
	8.4	15.7	0	0	0	0	80
	13.0	19.1	0	0	0	0	100
	16.3	21.5	0	0	0	0	120
	18.7	23.2	0	0	0	0	140
	20.6	24.6	0	0	0	0	160
	0.0	12.6	0	0	0	0	40
	1.3	12.1	0	0	0	0	60
	8.4	11.4	0	0	0	0	80
U.S. EPA	12.3	15.0	0	1.3	0	1.6	116
U.S. EPA	12.3	15.0	13.5	1.3	0	0	116