Economic impacts of the U.S. Renewable Fuel Standard: An *ex-post* evaluation

By

Farzad Taheripour, Harry Baumes, and Wallace E. Tyner

Authors' Affiliation
Farzad Taheripour is Research Associate Professor and Wallace E. Tyner is James and Lois Ackerman Professor of Agricultural Economics in the Department of Agricultural Economics at Purdue University. Harry Baumes is the Chief Executive Officer of the National Center for Food and Agriculture Policy

Corresponding Author
Farzad Taheripour
Department of Agricultural Economics
Purdue University
403 West State St.
West Lafayette, IN 47907-2056
765-494-4612
Fax 765-494-9176
E-mail: tfarzad@purdue.edu

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Abstract

This paper examines the extent to which biofuel production has been driven over time by the U.S. Renewable Fuel Standard (RFS) and the extent to which it was driven by non-RFS policies and market forces. While the RFS has played a critical role in providing a secure environment to produce and use more biofuels, at least in the 2000s, it was not the only factor that encouraged the biofuel industry to grow. While, the existing literature has successfully identified the key drivers of the growth in biofuels, it basically has failed to properly quantify the impacts and contributions of each of these drivers separately. This paper develops short and long run economic analyses, using Partial Economic (PE) and Computable General Equilibrium (CGE) models, to differentiate the economic impacts of the RFS from other drivers that have helped biofuels to grow. Results show: i) the bulk of the ethanol production prior to 2012 was driven by what was happening in the national and global markets for energy and agricultural commodities and by the federal and sometimes state incentives for biofuel production; ii) the medium to long run price impacts of biofuel production were not large; iii) Due to biofuel production, regardless of the drivers, real crop prices have increased between 1.1% and 5.5% in 2004-11 with only one-tenth of the price increases were assigned to the RFS, iv) For 2011-16, the long run price impacts of biofuels were less than the time period of 2004-11, as in the second period biofuel production increased at much slower rate, v) Biofuel production, regardless of the drivers, has increased US annual farm incomes by $10.6 billion between 2002-16 with 28% share for the RFS.

Keywords: Renewable Fuel Standard, Biofuels, Food and Crop Prices, Economic Impacts, Partial and General Equilibrium

1. Introduction

The relationship between the U.S. Renewable Fuel Standard (RFS) and commodity and food prices is very complicated. Part of the complication is the questions of attribution. Some of the early literature tended to blame the RFS for all increases in commodity prices. However, over time it has become abundantly clear that many factors have been involved in the evolution of commodity and food prices, with the RFS and biofuel production in general being only one.

The original RFS was enacted by Congress in 2005 [1]. The RFS was amended in 2007, and the revised and current RFS is sometimes referred to as RFS2 [2]. However, in this paper, we will refer to it as RFS. The major objectives of the RFS were 1) to provide a source of increased incomes and employment in rural areas, 2) to increase US energy security, and 3) to reduce greenhouse gas (GHG) emissions [3]. However, prior to the enactment of the RFS, there was other legislation related to ethanol, which is summarized by Tyner [4]. The National Energy Conservation Policy Act [5] was essentially the first piece of renewable energy legislation and established an excise tax exemption for ethanol of $0.40/gal.[1] This tax incentive was converted to a Volumetric Ethanol Excise Tax Credit (VEETC) in the American Jobs Creation Act of 2004 [6]. The government support continued in some form through 2011 and varied between $0.40 and $0.60/gal. of ethanol. The use of government incentives and the RFS were the two main policy instruments aimed at helping to establish and grow the ethanol industry to accomplish the three aforementioned goals. However, as we will see below, there were many other factors that helped drive commodity prices between 1980 and today.

[1] The form and amount of the government support has changed over the years.

The food-fuel issue initially caught the public's attention in 2007-08 and again in 2011 when commodity and food prices rose substantially. In the literature review below, we will explore the key drivers of the commodity price increases and the extent to which they are related to the RFS and to biofuels. Also, it is important to note that even significant increases in agricultural commodity prices normally do not lead to significant increases in overall food prices because agricultural commodity prices are a small component of the overall food market basket.

The rest of this paper is organized into 4 additional sections. First, the literature review covers some of the key papers and summaries of key drivers of commodity and food price increases. There have been hundreds of papers related to this topic, so a comprehensive review of that literature will not be provided here. Rather, we will focus on the key themes developed later in the paper. Data on what was happening in the various markets will be integrated with the literature review to better depict what was happening in the markets to support the analysis that follows. We will present key data series such as crude oil and gasoline prices, ethanol production and prices, corn prices, and Renewable Identification Number (RIN) values. We will relate changes over the period being examined to the key drivers identified in the literature review. After the literature review, we explain the approach we will use in this analysis. After that we will present the quantitative results of our model simulations and relate them to the literature and data discussions. The last section cover the conclusions.

2. Literature Review

The literature review and data analysis are divided into five periods that are characterized by different drivers (Table 1). The first period is 1980-2004. The only ethanol incentive during this period was the ethanol tax exemption. However, the Clean Air Act Amendments of 1990 also provided some demand for ethanol as a source of oxygen in gasoline [7].The first RFS was passed in 2005, but as we will explain below, it was not ever really binding. A mandate is considered to be binding if it results in changes in production from what the market would have produced absent the mandate. In the case of the RFS, an indication of the extent to which the RFS is binding can be the price of RINs. If they are very low, it means the RFS is not playing a major role in determining production levels. The second period is 2004-2008. Lots of things were changing during this period, and the first real push on the food-fuel issue was around 2008. Then at the end of 2008 and into 2009, the great recession occurred, and most of the key drivers changed. In 2010-2011 commodity prices moved up again with a variety of drivers behind the change. The final period is 2011-2016.

In addition to dividing the literature and data analysis into these periods, we will also discuss other papers that provide a somewhat different take on the RFS such as one by Abbott [8]. We also will cover other important papers that examine the time varying relationship between biofuels and commodity and food prices. The literature review concludes with a summary of key points to be considered in the analysis that follows.

<Table 1 Here >

Figure 1 shows annual ethanol production from 1980 through 2017. It is clear from that figure as well as other information that many of the key drivers of what was happening in energy, agricultural, and biofuel markets followed the period breakdown provided above. That is, the drivers changed from one period to another, and it is important to understand how the changing drivers impacted what was happening in markets through time. During the first period (prior to 2004), there was slow but steady growth in ethanol production driven mainly by the ethanol tax incentive and demand for oxygen provided by ethanol in gasoline blends. The exception was 1996 when the 1995/96 corn crop was limited by a 7.5% set-aside program and poor yields due to dry weather. Corn prices rose in the face of good demand, but supplies were limited, and corn ethanol production dropped 20% (270 mil. gal.) from 1995 to 1996. From 2004 to 2008, the second period, there were many market related drivers of ethanol production growth, and the RFS came into effect. In 2009 and 2010 ethanol production continued to grow but fell in 2011 and 2012 again due to a different set of key drivers. Then ethanol production continued to grow at a smaller rate through the next period.

<Figure 1 Here>

Prior to 2004

Figure 2 shows monthly crude oil prices for the period 1980 to present. The time period identified by the oval in Figure 2 represents the early years of the ethanol biofuel program. During that time, the only government incentive for ethanol production was the tax exemption, which varied from 40 to 60 cents/gal. depending on the legislation in effect [4]. There was no RFS. This was also a time of low oil prices, with crude oil ranging from $10 to $33/bbl. between 1983 and 2003. Annual average of monthly corn prices also was relatively low ranging from $1.40 to $4.43/bu. over the entire period (see Figure 3). Excluding the high price year of 1996, the peak corn price was $3.36/bu., and they were much lower during most of the period. For example, the highest monthly corn price from 1997 to 2003 was $2.80/bu. There were also farm programs in existence during parts of this period, which provided farmers some non-market compensation. The bottom line is that the combination of very low crude oil (and gasoline) prices, relatively low corn prices, demand for ethanol as an oxygen additive, and the tax exemption was enough to stimulate growth in the ethanol industry from 415 million gallons in 1983 to 3.9 billion gallons in 2005, an annual growth rate of 9.5% with no RFS in effect [4, 10]. The ethanol tax incentive was the main driver of government policy and enabled the ethanol industry to be established. The first RFS was established in 2005, but production exceeded the RFS required levels. The second RFS was established in 2007, but again production/use was higher than the requirements, in the early years of the RFS.

<Figure 2 Here>

It is also important to note that the linkages among energy and agricultural commodities changed significantly over the course of the ethanol program. For example, from 1988 through 2005 the correlation between crude oil and gasoline prices was 0.97 as would be expected, whereas the correlation between crude oil and corn prices was -0.26 [12].There was no significant correlation between crude oil and the corn price during this early period. This lack of relationship is illustrated in Figure 3 [13]. It was only after crude oil and gasoline prices began to rise that a link with corn prices emerged. The correlation between monthly crude oil and corn prices over 2006-08 was 0.80. This link will be discussed further below.

The main conclusions from the pre- 2004 period are:

- There was no relationship between biofuel production and corn prices
- Ethanol production grew about 9% per year due to the ethanol tax exemption, relatively low corn prices, demand for ethanol as oxygen additive, and despite very low crude oil prices. The combination of these factors enabled this growth in ethanol production. There was no RFS during this period.

<Figure 3 Here>

<u>Period of 2004-2008</u>

The period 2004-08 was a critical period for the US ethanol industry. Over that period, ethanol production grew at a substantial 24% annual rate. Over this period, RFS was introduced, but it was never binding except perhaps for a few months in 2008 and extending into early 2009.

One indication of whether the RFS was binding or some other factors were influencing the market is the RIN price. Throughout this period, ethanol RINs were in general very close to zero, usually less than five cents per gallon. When RIN prices are low or near zero this indicates that the obligated parties can meet their required volumes without seeking additional RINs. Figures 4 and 5 illustrate a non-binding and binding RFS in standard economic demand and supply terms. With a binding RFS, the theoretical RIN price is illustrated by the distance between the demand and supply curves at the RFS level as shown in Figure 5. In that figure, the RFS level exceeds the quantity at the intersection of the supply and demand curve. Over the short term, many other factors such as RIN carry-forward, US Environmental Protection Agency (EPA) announcements, etc. also can influence the RIN price. When the RFS is not-binding (Figure 4), RIN prices are quite low, and essentially represent transactions costs among industry players [8] because market demand exceeds the RFS level and market price is higher than the RFS and supply curve intersection.

So why was the RFS not binding over this period when production was growing at such a fast rate? In general, it was because ethanol production was increasing basically due the market forces and non-RFS biofuel policies. These factors kept ethanol production levels ahead of the RFS mandated levels. As will be noted below, the RFS provided some incentive to build plants by guaranteeing a minimum level of use, but market forces were the key drivers. We will now examine some of these factors.

<Figure 4 Here>

<Figure 5 Here>

The first big pull was the rapid escalation in crude oil and gasoline prices. These prices are illustrated in Figure 6, which just shows that gasoline price follows crude oil price very closely.

The quantitative relationship between the two over this time period is given by the following ordinary least squares regression equation, which has an adjusted R^2 of 0.98:

Gasoline price ($/gal.) = 0.20 + 0.267 * crude oil price ($/bbl.)

Wholesale gasoline price went from $1.05/gal. in January 2004 to $3.35/gal. in July 2008. Gasoline price more than tripled in 4.5 years. Since ethanol and gasoline substitute for each other at the margin, the huge increase in gasoline prices also pulled up ethanol prices (Figure 7) and made investment in ethanol more attractive.

<Figure 6 Here>

Another key driver easily visible in Figure 7 was the effective methyl tertiary-butyl ether (MTBE) ban in June 2006. MTBE, a fuel additive, was an important source of both oxygen (to promote cleaner burning) and octane for gasoline. Ethanol was the only inexpensive substitute for the 5.0 billion gallon MTBE market for supplying the needed oxygen and octane. According to the US Energy Information Administration (EIA), ethanol blended at a 5.8% rate could provide the needed oxygen [14]. When MTBE was effectively banned (the Energy Independence and Security Act of 2007 did not provide protection from legal liability for MTBE toxicity issues), the price of ethanol shot up due to the increased demand. In turn, building ethanol plants became very profitable with a very quick payback period. Corn prices tended to move up with ethanol prices but not as fast as ethanol prior to 2008. As explained below there were some other important drivers that came into play around 2008 (Figure 8).

<Figure 7 Here>

<Figure 8 Here>

In a 2008 study, Abbott, et al. did a comprehensive analysis of the key drivers of commodity and food price increases in 2006-08 [17]. The authors provided a comprehensive annotated bibliography, so we will not delve into a lot of the literature covered in that report. That study has been cited over 650 times, so we consider it to be a good source for identifying and explaining key drivers of commodity and food prices as of 2008. That study concluded that the commodity and food price increases had three main sets of drivers for this time period:

- Global changes in production and consumption of key commodities
- The depreciation of the US dollar (exchange rate)
- Growth in production of biofuels

We will explore each of these sets of drivers in turn. First, with respect to global production and consumption of grains, the study focused on the extremely low level of grain stocks in 2007/08. In eight of the nine years prior to 2007/08 global grain consumption had exceeded production. Global incomes had been rising leading to higher grain consumption [18]. On the production side, weather and crop disease issues in different parts of the world in 2006-07 made matters worse. As a result, by 2008 the corn stocks-to-use ratio was the lowest it had been since 1973/74.

The second important driver was the depreciation of the US dollar from 2002 to 2008. Most commodities are priced in US dollars in global markets. That means that when the US dollar falls, the commodity prices in terms of other currencies falls, and consequently, demand for US exports rise. The declining dollar also contributed to the increase in oil prices because oil became cheaper for consumers in other parts of the world. In addition, there appears to have been what is termed a "financialization" of the commodity markets starting about 2002-03, which means that many of the internationally traded commodities moved together much more than in the past. The role of commodity market speculation in this change has been hotly debated, but there is no doubt financialization of commodity markets and exchange rate have been important drivers.

The third driver is the increase in production of biofuels. As described above, this increase in production of US corn ethanol was due mainly to market forces and not to the RFS. During most of this period, the RFS was not binding, meaning that drivers like the MTBE ban, increasing crude oil and gasoline prices, and the fixed per gallon ethanol tax incentive were the major forces incentivizing capacity building and increased production of biofuels.

In conclusion the commodity and food price increases in 2006-08 was a perfect storm of many forces in global commodity demand and supply, US dollar decline, and the market pull of higher crude oil and gasoline price and other factors in increasing ethanol supply, which led investors to build ethanol capacity ahead of the RFS mandate levels. Shrestha et al. did an analysis of food price increases from 1973 to 2016. They found that the food price increase was lowest during the 1991-2016 period, corresponding to the biofuels boom period [19].

Period of 2008-2009

The great global recession began in the fall of 2008 and hit its deepest in 2009. Many of the key drivers that had operated in the period leading up to 2008 went into reverse, but functioned in a similar manner [20]. Crude oil and gasoline prices plummeted with crude oil falling from $129/bbl. in July 2008 to $37/bbl. in January 2009. With reduced global incomes, demand for most commodities and their prices fell. With declining gasoline prices, the price of ethanol followed. However, ethanol production remained strong because corn price fell along with or even further than ethanol prices. The US dollar exchange rate that had depreciated leading up to July 2008 reversed course to appreciate against most world currencies. For example, the US dollar appreciated 24% against the Euro between July 2008 and November 2008. Even though the recession was quite deep, commodity prices generally began a rebound in 2009, which continued through 2011 as discussed in the next section. Throughout this period, ethanol RIN prices remained low suggesting again that the RFS was not binding in this period.

Period of 2010-2011

Commodity prices again rose in 2010-11 with crude oil topping $100/bbl. and corn around $7/bu. During this period, some of the key drivers from earlier periods remained, but there were also new drivers [21]. Poor harvests in several parts of the world were more important in 2011 than in 2008 leading to higher agricultural commodity prices. Leading up to 2011 there was also a significant change in Chinese policy with respect to soybean imports. With persistent demands for corn for biofuels and China for soybeans, overall price elasticity became more inelastic, which led to higher prices and more price volatility. With the higher demands for corn and soybeans at the same time, acreage in the US shifted towards those crops leaving less land for other crops like cotton, so the prices of other crops increased as well in 2011.

Ethanol and corn prices rose together in 2010-11. Blend wall concerns began to appear in 2011 [8, 22], but ethanol exports increased substantially over that period as shown in Figure 9. RIN prices continued at low levels indicating that the RFS still was not binding.

Another development that began around 2009 was that ethanol prices moved below gasoline prices (Figure 7) and appeared poised to remain low for some time. Many refiners saw this as an opportunity to reduce refining costs by producing lower cost 84 octane gasoline out of the refinery and blending with 10 percent ethanol to yield an 87 octane blend at the pump. In fact, ethanol prices did remain below gasoline for years to come, and that change increased the market demand for ethanol as an octane additive. In other words, ethanol became more a standard part of the gasoline refining system. Ethanol has higher value as a fuel additive (oxygen and octane) than as a fuel extender, but this value is difficult to capture in economic models. However, in a recent

FarmDoc Daily post, Scott Irwin quantified the added value ethanol provides as an octane enhancer [23].

<Figure 9 Here>

Period of 2011-16 and Beyond

In 2012, the US experienced a major drought, and corn production plummeted. In 2012-13 corn prices were high relative to ethanol prices (Figure 8) which led to negative ethanol margins according to the Iowa State Ethanol Profitability model and as illustrated in Figure 10 [16]. As a consequence, ethanol production declined (Figure 1) as capacity utilization fell. Also, ethanol exports declined over this same period (Figure 9).

Another significant change that occurred during this period was that the gasoline market moved towards the historical definition of the blend wall: the 10% maximum ethanol content[2] [22, 24]. When the revised version of the RFS was enacted in 2007, annual gasoline consumption was 142 billion gallons and was expected to continue to increase as it had in the past (approximately 1.3% per year). Had that happened, gasoline consumption would have grown to over 150 billion gallons annually by 2014 and would have absorbed the RFS level of 15 billion gallons of corn ethanol at a 10 percent blending rate definition. However, following 2007, gasoline consumption fell and did not even reach the 2007 level again until 2016 when it reached 143 billion gallons. Thus, the 15 BG RFS mandate could not be absorbed by the gasoline market at a historical 10% maximum ethanol content. The decline in gasoline consumption was due to two main factors. First, the great recession of 2008-09 led to a large drop in gasoline consumption, and consumption

[2] The perception, as well as the reality, of the 10% blend wall could be altered in future, and the national ethanol blend rate first surpassed 10% in 2017 and after that year. That is because the EPA has already approved E15 for use in cars built since 2001 and updated regulations to provide E15 parity with 10% blends in 2019. In addition, newer flex-fuel vehicles can use E85. Further change in market conditions in combination with proper fuel policies could extend demand for these types of fuels.

growth did not pick for a considerable amount of time. Second, the US enacted more stringent fuel economy standards, which meant consumers could drive more miles with less fuel. High oil and gasoline prices also encouraged consumers to purchase more fuel-efficient vehicles and perhaps to drive a bit less.

Because of the decline in gasoline consumption as described above, not enough ethanol could be blended at the historical 10% maximum ethanol content to achieve the implied RFS targets starting in 2013. Table 2 provides the adjusted RFS level by the EPA, actual gasoline consumption including ethanol (from EIA), our calculation of the pure gasoline (non-renewable gasoline), and the ethanol content based on the historical 10% blend rate definition. We used 10% because E85 and E15 consumption volumes were very small and not all gasoline is blended with ethanol[3], so essentially, we assume those offset each other. Table 2 clearly illustrates that the 10% limit for ethanol was lower than or about equal to the RFS level for each of these years. That is why biodiesel and other advanced fuels were used for part of the implied conventional biofuel requirement. It is important to note that the 2014 and 2015 RFS ethanol requirements were set after the fact and essentially matched actual consumption in those years.

<Table 2 Here>

<Figure 10 Here>

As mentioned before, prior to 2011, ethanol was basically in demand as a fuel extender and an octane additive. This changed after 2011 and a portion of ethanol was consumed as a substitute for gasoline to meet the RFS requirements, along with providing a source of octane. Since 2011, as the total consumption of ethanol moved towards the historical 10% maximum ethanol content (that was allowed in non-flex-fuel vehicles), demand for ethanol did not grow enough to meet the

[3] Recent evidence provided by the EIA indicates that the actual ethanol blend rate has exceeded the historical 10% blend rate after 2016.

minimum RFS requirement, and that led to higher RINs prices. Corn ethanol (D6) RIN prices had generally traded in the \$0.02 - \$0.04 range through 2012. Essentially, the RIN price was the transaction cost. The RFS was not really binding, and there were no major blending issues. Starting in 2013, the market observed major increases in the corn ethanol RIN values, topping \$1/gal. as shown in Figure 11. Originally EPA did not take the limit in demand for ethanol into consideration, and the RFS levels ended up in court. Consequently, the RFS mandate level for 2014 and 2015 ended up being established after the fact and essentially conformed to actual blending. Since then, EPA has gradually increased the implied requirement level of ethanol to the enacted legislated 15 billion gallons.

Starting in 2013 ethanol RIN prices moved up to biodiesel RIN prices and essentially followed biodiesel until recently as shown in Figure 11. Does that mean the RFS became binding? It does not. The historical 10% blend rate became the limiting factor until 2016. Due to the nested structure of the RFS, biodiesel and other advanced RINs could be used to satisfy the part of the conventional fuel (ethanol) requirement (adjusted and implied by the EPA) that could not be done with ethanol. Korting et al. argue that in addition to the RFS nested structure, the joint gasoline and diesel compliance base is also important [25].

<Figure 11 Here>

Thus, biodiesel became the marginal means of fulfilling the conventional biofuel mandate. In economics, everything is priced at the margin, so the ethanol RIN price rose to the level of the marginal means of fulfilling the conventional mandate which was biodiesel represented by the D4 RIN price. That continued until 2018. The link weakened in 2018 because EPA issued large amounts of small refinery RFS waivers. That action effectively lowered the implied conventional corn ethanol requirement (RFS) to the historical 10% blend rate or less. That dropped the ethanol

RIN price down to nine cents in 2019. The EPA granted additional small refinery waivers in 2019, which effectively lowered the RFS and put additional downward pressure on RIN values.

Another important change in energy markets that occurred during this time period is the shale oil boom [26], which led to a 57% increase in US crude oil production between 2011 and 2016 (Figure 12). This remarkable increase in US production helped push world crude oil prices lower as shown in Figure 2. In addition, energy prices in general have fallen about 37% since 2011 [27]. Energy consumption increased slightly (0.5%) between 2011 and 2016, but energy expenditures fell 34% because of the fall in prices. In fact, in 2016 energy expenditures as a share of GDP (5.6%) were the lowest since 1970 [28].

<Figure 12 Here>

Time varying relationships among commodity prices

In addition to the studies mentioned above, USDA has published some important papers on the food-fuel issue [18, 30]. The USDA Chief Economist, Joseph Glauber provided important Congressional testimony indicating that agricultural commodity costs on average represent only 14% of the food dollar [31]. There have been many econometric studies of the relationships among prices of crude oil, gasoline, ethanol, corn, and other commodities [32-35].

Filip et al. [33] provide a review of much of the econometric literature through 2017, so we will not repeat that here. Their paper, in addition to providing a comprehensive literature review of the econometric studies, also provides an updated econometric analysis of the Zhang, et al. 2010 paper [35]. Zhang et al. concluded that there was only a weak relationship between ethanol and agricultural commodities between 1989 and July 2008 (see Figure 3). Filip et al. used a significantly expanded data set covering many more commodities and other variables such as exchange rates, interest rates, and stock indices. Their data set runs from November 2003 through

May 2016. They find that ethanol did not affect agricultural commodity prices prior to the 2008 food crisis. During the food crisis periods, they estimate that about 15 percent of the variance in corn prices was due to ethanol and 5 percent of other commodities. In years after the food crisis, they find that ethanol contributed about 10 percent of the variability in agricultural commodity prices. Their main conclusion is that biofuels did not serve as a leading source of high commodity prices and that the price links varied over time with what was happening in the markets. The authors assert that their results serve as an "ex-post correction" of the previous results suggesting dramatic effects of biofuels on commodity and food prices [36, 37]. However, as indicated above, they do find some influence during and after the 2008 and 2011 food crisis periods. It is important to note that this analysis does not separate impacts of the RFS from other market factors driving biofuels. It is just an analysis of the impacts and commodity price linkages due to biofuels regardless of whether the biofuels were driven by market forces or the RFS or some combination.

Chiou-Wei et al. [32] in a 2019 study also concluded that the relationships among crude oil, natural gas, ethanol, corn, and soybean prices were time-varying. Their data series ran from March 2005 through October 2017. In their analysis, they estimated structural breaks in the markets for each of the commodities with the last period generally beginning in 2013/14. They find that in recent years, the connections among the markets were relatively weak.

Abbott [8] used data from 2005 through 2012 and divided the analysis into six different periods defined by examination of constraints that were binding in each period. He found remarkable differences in the crude oil and corn price correlations. In the period he calls the ethanol gold rush, he found a negative correlation of -0.13, which is consistent with the negative -0.25 Tyner obtained for the 1988-2005 period [12]. For what he called the food crisis and great recession periods, Abbott calculated correlation coefficients of 0.94 and 0.96, respectively. For similar periods Tyner estimated crude oil–corn correlations of 0.80 and 0.95. Abbott found that the correlations then dropped substantially in the two following periods. Of course, these are correlations and do not imply causality. Abbott was more interested in examining the constraints that were binding in each period. He found that ethanol capacity constraints were binding in most of the periods, meaning that the supply for corn ethanol was limited by the production capacity. He also found that the RFS influenced capacity additions but did not bind ethanol refiner behavior. Capacity always increased ahead of the RFS mandate levels.

The gist of the recent econometric work is that biofuels played a small but not negligible role during the commodity and food price run-up periods of 2008 and 2011. All the recent studies also show that the links among crude oil, gasoline, ethanol, and corn prices varied significantly over time depending on what else was happening in the markets, which is consistent with our analysis of key commodity price drivers above. Also, many of the studies concluded that whatever influence biofuels had on agricultural commodity prices was more important in the short run than in the long run [31, 33]. None of the econometric studies distinguish between market and RFS drivers of commodity prices, but Abbott concluded that the RFS did not bind refiner behavior during his analysis period, which is also consistent with our analysis. Chiou-Wei et al. concluded that connections among the markets were relatively weak in recent years, which is consistent with the results from Filip et al.

RFS and Commodity Prices

Two other papers have appeared recently that claim to establish a relationship between the RFS and commodity prices. The first by Carter et al. examined only corn [38], while the second used a similar approach but added soybean and wheat markets [39]. Carter et al. argued that corn prices were about 30% higher in 2006-14 than they would have been without the ethanol demand increase. Their approach was to try to separate transitory shocks (weather, etc.) from permanent shocks (e.g., RFS). Their model only included corn inventory and cash and futures corn prices. It did not include crude oil or gasoline prices, any proxy for the global demand drivers described above, or any other ethanol demand driver. The analysis simply assumed that the sole demand driver was the RFS and not the other economic and market drivers described here. For example, the model did not include the 2006 MTBE ban, which as a permanent shock would have in their analysis been attributed to the RFS. Similarly, they did not include the fact that in 8 of the 9 years prior to 2008 (most of which were pre-RFS), global consumption of cereal grains exceeded production, resulting in extremely low stocks-to-use ratios. That also would be a permanent shock, which in their framework gets attributed to the RFS. Same thing applies to the demand for ethanol for octane 2009-2016 - another permanent shock that in their framework gets attributed to RFS. Thus, the analysis reported in this paper is not relevant here because it simply assumed the demand driver was the RFS. The second paper by Smith followed the same approach, and, therefore, is not considered relevant for this paper.

Conclusions from the literature review and data examination

The main take-away from this section is that most of the analyses that have been done to date do not distinguish between market drivers of ethanol production growth and the RFS as a driver. In the 1980s and 1990s, ethanol tax incentives and the Clean Air Act Amendments of 1990 which established reformulated gasoline were the key policies enabling establishment and relatively slow growth of the industry during a period of low crude oil prices. In the years 2004-08, there was a substantial run-up in crude oil prices that pulled ethanol into the market. The crude oil price increase and the 2006 MTBE ban were the key drivers in capacity additions. Ethanol margins were strong in 2005-07, which provided strong incentives to add capacity. Of course, the added ethanol production increased demand for corn and was part of the reason for the corn and other commodity price increases. Filip et al. estimate that biofuels may have been responsible for about 15 percent of the rise in corn prices. But that was biofuels production induced primarily by market forces, and the ethanol tax incentive. Price correlations continued strong through the recession and the second commodity price surge in 2011. The 2012 drought reduced US corn production, and higher prices sent ethanol margins negative and led to a temporary drop in ethanol production. The short run impact of biofuels on commodity prices may have been more important in late 2008 and early 2009. Since 2013 RIN prices increased rapidly due to constraints on the growth of ethanol consumption, as the market moved towards the 10% historical blend rate. Ethanol exports started a growing trend in 2013 that continues today.

This is a story of biofuels production being driven mainly by market forces and government support for ethanol, which ended in 2011. Prior to this year, the RFS provided an incentive to get capacity built and also generated a safety net for biofuels to grow, but it was not binding in the markets except for a few months in 2008-09. Since 2011 the RFS in combination with constraints on the growth of ethanol consumption drove the markets for biofuels. Finally, the recent econometric evidence suggests that biofuels were not the main driver of commodity price increases.

An interesting question to ask given our conclusions on the role of markets in driving biofuels growth is how it would have been different if all these market changes had not occurred. In other words, what if crude oil price had not surged, MTBE had not been banned, ethanol did not get integrated into the fuel system becoming a fuel additive instead of a fuel extender, etc.? The answer is clearly that the RFS would have played a much greater role. So, in a sense, the RFS has been the backstop, but by circumstance, it was overpowered by tax incentives and market forces through 2011.

Another interesting comparison is between what happened over this period for ethanol compared with biodiesel and cellulosic biofuels. For both biodiesel and cellulosic biofuels, the RFS was clearly an important driver of production and consumption. RIN prices were always relatively high, and the RFS was always binding. Clearly, the market changes that benefitted ethanol did not work as much in favor of these other biofuels.

3. Method

To assess the annual, short run, and long run price impacts of the US RFS, in this research, we make use of both a Computable General Equilibrium (CGE) model and a Partial Equilibrium (PE) model. Each modeling approach has advantages and disadvantages, and we use each model relying on its unique strengths and fit for the question(s) being asked. In general, GTAP-BIO is used for the global and longer-term analysis, whereas the PE model is used for specific analysis of the US agricultural and liquid fuel sectors to capture finer and shorter-term impacts. The combination of the two modeling frameworks permits us to analyze and evaluate all the important issues related to biofuels, RFS, and commodity and food prices. We use the models iteratively in the analysis to gain the advantages of both approaches.

CGE Model

To accomplish the goals of this research, following our earlier work, we will use a well-known global CGE model: GTAP-BIO. This model is an advanced version of the standard GTAP model. The standard model is fully described in Hertel [40]. GTAP-BIO extends the capabilities of the standard model to develop economic and land use analyses related to the environmental, agricultural, energy, trade, and biofuel policies and actions. This model has been improved over time and used in various applications [41-48]. Taheripour et al. [49] described the background of this model and Taheripour et al. [50] developed the latest version of this model. Figure 13 represents the model major components.

This model traces production, consumption, and trade of all goods and services (aggregated into various categories) at the global scale. Unlike the standard model, GTAP-BIO disaggregates oil crops, vegetable oils, and meals into several categories including: soybeans, rapeseed, palm oil fruit, other oil seeds, soy oil, rapeseed oil, palm oil, other oils and fats, soy meal, rapeseed meal, palm kernel meal, and other meals. In addition to the standard commodities and services, this model integrates the production and consumption of biofuels (e.g. corn ethanol, sugarcane ethanol, and biodiesel) and their by-products (DDGS and meals). Therefore, unlike the standard GTAP model, the enhanced model takes into account the use of commodity feedstocks for food and fuel and the competition or trade-offs between those and other market uses. In addition, it traces land use (and changes in land prices) across the world at the level of Agro-Ecological Zone (AEZ). The latest version of this model handles intensification in crop production due to technological progress, multi-cropping, and conversion of unused cropland to crop production. Finally, the parameters of this model were calibrated to recent observations. This model traces the inter-relationships among crop, livestock, feed, and food sectors and links them with biofuels sectors and accounts for upstream and downstream linkages among these sectors and other economic activities. This model also considers resource constraints and technological progress. Hence, it provides a comprehensive framework to assess the price impacts of biofuel production and policies. While the GTAP-BIO model produces global outputs, for the purposes of this analysis, we focus on the US impacts.

<Figure 13 Here>

PE model

The CGE analyses introduced above provide comprehensive and overall medium to long run analyses of the price impacts of the US RFS and do not include short run and annual price changes induced by the US RFS or other factors. The literature is rich with explanations of key drivers of price changes that may not be included in medium to long-term models. A good example is the series of Farm Foundation papers that explain how the drivers of commodity and food price changes over the period 2008-2011 [17, 20, 21]. To provide short run and annual analyses we will use an improved version of an Agricultural Energy Partial Equilibrium (AEPE) model which was developed by Taheripour and Tyner and used in several publications cited above to examine interactions between agricultural and energy markets and evaluate the consequences of changes in biofuel policies. The improved version of the model covers crude oil, gasoline, corn ethanol, biodiesel, corn, soybeans, and feed (e.g. DDGS and meals) markets. The model is for the US economy. It distinguishes demand for corn and soybeans in their alternative uses (food, feed, biofuels, and exports) and traces changes in agricultural subsidies and biofuel policies.

The AEPE model uses a base year data set, short run demand and supply elasticities for the (commodity) markets included in the model, and long run and short run shift factors in demand and supply of each market and determines their new equilibriums over time. The long run and short run shift factors are exogenous to this model. The long run shift factors (e.g. population, income growth, and growth in demand for livestock products) help the model to adjust overtime. The short run shift factors represent annual exogenous changes (e.g. reductions in crop yields due to a drought). We have used this model for the time period 2004 to 2016 to better characterize short run changes in the agricultural and fuel markets over this period. Some of the shift factors are directly observable, while others may not be directly observable. For example, historical data represent annual fluctuations in crop yields or changes in ethanol incentives are directly observable. The PE model takes into account these shift factors through its exogenous variables. For unobservable shift factors (e.g. shift factors in the demand of energy or shifts in foreign demand for corn), we will rely on the outputs of the GTAP-BIO model and other observations as discussed later in this paper.

Over-all modeling approach

In essence, we use the AEPE model to provide more detailed results for the US than is possible from a global CGE model. The combination of the CGE and PE models and their results enables us to respond to most the goals of this project. Figure 14 represents our modeling approach and the links between the CGE and PE models. The CGE model results are used to assess the medium to long run price impacts of biofuels. The PE model assesses the annual and short term price impacts of biofuels, including corn ethanol and soybean biodiesel. This figure shows interactive links between the CGE and PE models through the shift factors.

Examined experiments

As described above, the main goal of this research is to answer the following two important questions:

- To what extent the US RFS alone has affected commodity and food prices,
- To what extent the expansion in US biofuel production has affected commodity and food prices, regardless of the causes.

To answer these questions, we developed historical simulations and counterfactual experiments using the CGE and PE models. Essentially, we modeled what happened in the agricultural and energy sectors due to all causal factors. Then, we removed the RFS to determine what the impact of the RFS had been isolated from all the other market drivers of changes in these markets. Then, we removed biofuels production increases to determine what had been the impact of biofuels (whether driven by the RFS or other factors). In each case, the difference between the simulated historic baseline and the experiment gives us the impacts on prices, production, etc., due to the one factor that was being altered. The historical simulations capture and represent changes in economic variables as happened in the real world. The counterfactual experiments repeat the baseline simulations under alternative assumptions to capture the RFS/biofuel impacts from the impacts of other drivers. In what follows we describe the baselines and counterfactual experiments, first for the CGE approach and then for the PE method.

CGE baselines and counterfactual experiments

During the time period of 2004-2016, crop and food prices followed increasing trends until 2012 and then traced downward paths or remained relatively flat in the US. One can observe a similar pattern globally as well. Given this observation, since the main goal of this research is to determine the impacts of the US RFS on crop and food prices, we split the CGE analyses into two distinct time segments of 2004-2011 and 2011-2016 to better understand the differences between the price determining forces of these time periods. Therefore, for each of these time slices we developed a historical baseline and several counterfactual experiments.

A historical baseline in a typical static CGE analysis captures and represents changes in the global economy for a given observed time period, say 2004-11 or 2011-2016 in our analysis. To construct a historical baseline using a static CGE model, we exogenously shock the model for a given set of variables (including macroeconomic and policy variables) and allow the model to determine changes in the production, consumption, and trade for all goods and services (including crops and food items) and also prices by region[4]. A baseline simulation usually takes into account

[4] Yao, Hertel, and Taheripour [48] have followed this approach and developed a static historical baseline for the time period of 2004-11 for a different application. For details see the appendix of the paper.

technological progress in production of goods and services as well. Changes in Total Factor Productivity (TFP) and improvements in productivities of the primary and intermediate inputs usually represent technological progress.

To construct the baseline for each time period we closely followed the approach used by Yao, Hertel, and Taheripour [48]. These authors developed a static historical baseline for the time period of 2004-2011 for a different application. Following these authors, in constructing the historical baseline for each time period, we exogenously shocked the model for the regional observed changes in population, gross domestic product (GDP), capital formation, labor force, managed land, biofuel production and policy, and agricultural and trade policies. We then allow the model to determine changes in the production, consumption, and trade for all goods and services (including crops and food items) and also prices by region. Given these exogenous shocks, the model determines TFP by country[5]. Given that technological progress in agriculture is a key driver of crop prices, we use observed changes in crop supplies to determine the rate of technological progress in crop sectors[6]. As mentioned in the literature review section, there were major shifts in crop demands between 2004 and 2016. Hence, in addition to the changes in crop yields, some demand shifters were introduced in the simulation processes for crop demands. Finally, the crude oil industry has changed significantly over the period 2004 to 2016. Since GTAP cannot capture these changes endogenously, we added proper shifters (shocks) to capture major

[5] The standard GTAP model endogenously determines GDP for given changes in primary factors of production and TFP. In the baseline simulation we shock the model for the observed changes in GDP and primary factors of production. This allows us to alter the model closure to determine TFP for the given changes in GDP and primary factors of production. This is a standard approach for estimating TFP by country using a CGE model.

[6] The Standard GTAP model uses production functions to determine crop supplies. The production function of each crop determines supply of that crop for given inputs (including intermediate and primary inputs) and rates of unbiased and biased technological progress. The rate of unbiased technological progress for each crop acts as a shift factor in the supply function of that crop. In our baseline simulation we will ask the model to determine these crop specific shift factors for the observed changes in crop supplies.

changes in the oil market exogenously. Finally, as mentioned in the next section we obtained data from credible sources including but not limited to the World Bank, Food and Agricultural Organization of the United Nations (FAO), Organization for Economic Cooperation and Development (OECD), and USDA to calculate the implemented shocks for the baseline construction process of each time period.

To isolate the price impacts of the US RFS from all other drivers that may affect production of biofuels we developed the following counterfactual experiments:

Experiment I: The historical baseline, among all drivers, captures the impacts of biofuel production on commodity and food prices. However, a portion of ethanol produced in the US was not used domestically. In 2011 and 2016 the US net export of ethanol was about 1 billion gallons and 1.1 billion gallons. Given that the RFS targets domestic consumption of ethanol, we eliminated the impacts of trade of ethanol form the historical baseline of each time period. In this experiment we freeze trade of ethanol to remain at its initial levels in the base year for each time slice. The difference between this experiment and the historical baseline captures the trade impacts of biofuels. Henceforth, we refer to this counterfactual experiment as: *Baseline with RFS.*

Experiment II: This experiment repeats the first experiment (*baseline with RFS*) while removing the restriction on ethanol consumption and allows market forces to determine ethanol consumption. Henceforth, we refer to this experiment as: *Ethanol free of mandate*. For each time period, the difference between the first and second counterfactual experiments represents the impacts of RFS for conventional ethanol.

Experiment III: This experiment repeats the first counterfactual experiment (*baseline with RFS*) while removing the restriction on consumption of both ethanol and biodiesel and allows market forces to determine consumption of these biofuels. Henceforth, we refer to this experiment as: *No*

RFS. The difference between the first and third counterfactual experiments represents the impacts of RFS for both ethanol and biodiesel.

Figure 15a provides a schematic picture for these counterfactual experiments and their relationships with the historical baseline for each time period of 2004-11 (left panel) and 2011-16 (right panel). Consider the left panel of this figure, which represents the historical and counterfactual simulations with the solid black lines. The vertical axis shows the price of a representative product. For example, P_{2011}^{2} and P_{2011}^{4} indicate the projected price of this product in 2011 for the *baseline with RFS* and *No RFS* cases. The difference between these two prices represents the impact of RFS on the price of the representative product for the time period of 2004-11.

<Figure 15a Here>

We now introduce the counterfactual experiments that capture the impacts of expansion in biofuel production, regardless of the causes. The following two counterfactual experiments were examined to accomplish this task:

Experiment IV: This experiment repeats the historical baseline, while it freezes production of ethanol at its base year level for each time period. The difference between this experiment and the historical baseline captures the impacts of expansion in ethanol production. Henceforth, we refer to this counterfactual experiment as: *No expansion in ethanol.*

Experiment V: This experiment repeats the historical baseline, while it freezes production of ethanol and biodiesel at their base year levels for each time period. The difference between this experiment and the historical baseline captures the impacts of expansions in ethanol and biodiesel. Henceforth, we refer to this counterfactual experiment as: *No expansion in biofuels.*

Figure 15b provides a schematic picture for the last two counterfactual experiments and their relationships with the historical baseline for each time period of 2004-11 (left panel) and 2011-16 (right panel). Consider the left panel of this figure which represents the historical and counterfactual simulations with the solid black lines. The vertical axis shows the price of a representative product for each experiment. For example, $P_{2011}^{1}$and P_{2011}^{6} show the price of this product in 2011 for the *historical baseline* and *No expansion in biofuels cases*. The difference between these two prices represents the impacts of the expansion in biofuel production on the price of the representative product for the time period of 2004-11.

<Figure 15b Here>

For the PE simulations we followed the same principle as well. First, we developed a baseline to replicate annual changes in the US markets for gasoline, ethanol, biodiesel, corn, and soybeans and their trade. To accomplish this task, we first calibrated the model to represent actual observations for 2015. We then run the model annually for a set of exogenous variables (e.g. crude oil price, ethanol trade, and targets for biofuel production) and tuning parameters to trace annual changes that occurred in the energy and agricultural markets. Then for each year we developed a counterfactual experiment to evaluate changes in the energy and commodity markets without targeting ethanol production. Hence, for the PE model we have only two cases: A *historical annual baseline* and a *market counterfactual* case which does not target production of ethanol.

Shift factors

The shift factors were determined using an iterative approach between the CGE and PE models and model parameters. We first run the CGE model for 2004-11 and 2011-16 with no shift factors. We learned that for both time periods the model needs shift factors to accurately represent crude oil markets. Using actual observations, we defined shift factors to replicate changes in the crude oil price exogenously. The shift factors indeed capture changes in the global market for crude oil that economic models fail to capture. One example is production of crude oil from shale resources in the US, which altered the global market for this product.

When we ran the PE model for annual changes we found as expected that the structure of demand for gasoline changes required demand shifters. First, there was the recession, which caused a major downward shift in gasoline demand. Then, the fuel economy standards began to take hold, which also caused a downward shift in gasoline demand. In fact, US gasoline demand did not catch up with the 2007 level until 2016. We developed shifters to represent these exogenous changes in gasoline demand. These shifters developed for the PE model also helped us to calibrate shifters in the gasoline market for the GE model.

In modeling the annual changes in the US markets for corn and soybeans, it became apparent that there were some exogenous shifts in international trade that could not be captured in the standard model. The best example is the very large increase in Chinese imports of soybeans, which was mainly due to policy changes that are not captured in the model. To take care of these changes we included demand shifters to represent changes in the global demand for these products.

Collected data

To support simulations, data on macro variables including GDP, population, labor force, investment, and GDP deflator were collected from the World Bank data base. A summary of macro variables is presented in Table 3.

<Table 3 Here>

The GTAP database has data on crop production and harvested area by crop for 2004 and 2011. We prepared the same data for 2016 using data from the Food and Agricultural Organization

(FAO) of the United Nations. Table 4 provides a summary of crop production and harvested area for the US and the rest of the world for the two time periods. While the model traces all crop categories included in the data bases, for this table we aggregated crops into three main categories including coarse grains (covering all coarse grains except sorghum), soybeans, and all other crops. Sorghum is included in the other category. The category of coarse grains basically represents corn.

In addition to these data items we collected a wide range of monthly and annual data on crop prices; prices of crude oil, gasoline, and ethanol; trade of agricultural products; and etc. to support our analyses and/or to be use in our simulations or to be compared to our results.

<Table 4 Here>

4. Results

CGE model results

As mentioned, we developed a historical baseline and several counterfactual experiments for each time period of 2004-11 and 2011-16. In this section we highlight the following results for each time period:

- Impacts of removing RFS only for corn ethanol: The difference between the results of *Baseline with RFS* and *Ethanol free of mandate* (i.e. difference between experiments I and II),
- Impacts of removing RFS for corn ethanol and biodiesel: The difference between the results of *Baseline with RFS* and *No RFS* (i.e. difference between experiments I and III),
- Impacts of no expansion in corn ethanol: The difference between the results of *Historical baseline* and *No expansion in ethanol* (i.e. difference between the historical baseline and experiment IV),
- Impacts of no expansion in biofuels: The difference between the results of *Historical baseline* and *No expansion in biofuels* (i.e. difference between historical baseline and experiment V),

Before presenting the results of these experiments, as a measure of validation, we compare the results of the historical simulations on the US crop prices for the time periods of 2004-11 and 2011-16 with their corresponding actual observations in Figure 16. This figure represents changes in crop prices in real terms. Given that GTAP represents real prices, the GDP price deflator is used to convert nominal observed prices to real prices. The left panel of this figure shows that crop prices have increased sharply between 2004 and 2011. This panel also shows that the model projections are in general very close to the actual observations. For this time period, there were somewhat greater differences between the actual observations and model simulations for wheat and rice. The right panel of Figure 16 shows that, unlike the first time period, crop prices have declined largely during the time period of 2011-16. This panel also shows that the model projections are in general very close to the actual observations. For this time period, there was only somewhat greater difference between the actual observation and model simulation for wheat. Hence, in general, the model projections for changes in crop prices are fairly in line with actual observations.

<Figure 16 Here>

Results for 2004-2011 time period

The mandated level of ethanol for 2011 is 12.6 BG. When we remove this mandate, the market determines consumption of ethanol, and it falls to about 12 BG. This means that the RFS on ethanol basically boosts consumption of ethanol by about 0.6 BG for the first time period. This projection is consistent with findings of the existing literature that non-RFS drivers including higher crude oil prices, tax incentives, added demand for oxygen and octane, and banning consumption of MTBE pave the way for ethanol industry to grow during this time period. In the

PE section results, we will explain that in each year of this period, in general, the RFS was not binding except for short period in 2008 and 2011.

When we remove the mandate on both ethanol and biodiesel, the consumption of ethanol drops slightly more by 0.7 BG. This means that the biodiesel mandate may have had a minor positive impact on corn ethanol expansion in this time period.

We now analyze the impacts of RFS on commodity outputs and prices. First consider the impacts on commodity outputs presented in the first two numerical columns of Table 5. The first numerical column is for removing ethanol mandate, and the second one is for removing both ethanol and biodiesel mandates. The results show if there was no mandate on ethanol, farmers produce less coarse grains (basically corn) by 1.2% and slightly more of other crops. When we remove both mandates on ethanol and biodiesel, outputs of coarse grains, soybeans, rapeseed, and other oilseeds drop by 1.4%, 1.6%, 12.4%, and 4.3% while outputs of all other crop categories grow slightly. From these results we can conclude, ignoring the contributions of non-RFS factors, the impact of RFS on crop production was very small. However, it encouraged farmers to produce more corn and oilseeds. Later in this section we discuss the overall impacts of biofuel production due to all drivers that encouraged biofuel production.

Regarding the commodity price impacts of RFS, consider the first two numerical columns of Table 6. The first numerical column is for removing ethanol mandate and the second one is for removing both ethanol and biodiesel mandates. The results show minor impacts in each case and for each crop category. For example, removing ethanol mandate lowers the price of coarse grains and soybeans by 0.3% and 0.1%. When we remove both mandates then these prices fall by 0.6% and 0.7%. The price impacts are also small for all other crop categories.

<Table 5 Here>

Now consider the overall impacts of biofuel production due to all drivers that encouraged producing more biofuels. The impacts on commodity outputs are presented in the last two columns of Table 5. The results show that if there was no expansion in ethanol farmers produce less coarse grains (basically corn) by 20.8% and more of all other crops. With no expansion in ethanol and no expansion in biodiesel, regardless of the drivers, outputs of coarse grains, rapeseed, and other oilseeds drop by 20.8%, 11%, and 3.6% while outputs of all other crop categories grow slightly. From these results we can conclude that biofuel production encouraged farmers to shift to produce more coarse grains (corn) and oilseeds. The impact for corn was large for the first time period. This is consistent with actual objections that confirm changes in the mix of crops produced in the first time period in favor of corn.

Regarding the commodity price impacts of biofuel production consider the last two columns of Table 6. The results show a reduction of 5.3% in the price of coarse grains with no expansion in corn ethanol. The price of coarse grains declines by 5.5% with no expansion in corn ethanol and no expansion in biodiesel.

Results of the CGE modeling practice for the first time period indicate that, in general, the RFS had minor impacts on crop prices. However, the price impacts of the expansion in biofuels were noticeable. For example, our analysis indicates that if there was no expansion in corn ethanol in this time period, supply of corn was lower by 20.8% and price of corn was lower by 5.3%. That means that the expansion in corn ethanol in this time period caused a 20.8% increase in supply of corn ethanol with 5.3% increase in the price of this commodity. A 20.8% increase in supply for 5.3% increase in price represents a relatively elastic supply of corn. In what follows we further explain this outcome.

<Table 6 Here>

Consider Figure 17, which presents short run and long run changes for the corn market. At the status quo the market operates at point *A*, with corn price of P_A and quantity of Q_A. The initial supply and demand curves are presented by S_A and D_A, respectively. An increase in corn ethanol, in the short run, shifts the demand for corn to D_B. With the initial supply curve (S_A) and the new demand (D_B) one may think that the market would move to point *B* with the higher price of P_B and production of Q_B. However, that would not happen in the real world as market mediated responses begin to act. First, the demand for corn in non-ethanol uses will drop due to higher prices, and that shifts the overall demand for corn downward to D_C. Then the supply of corn will increase over time in response to higher corn prices. Therefore, the supply curve of corn shifts to S_C. With these changes, the market moves to a new equilibrium at point *C* with supply of Q_C and price of P_C. Clearly, the price of P_C is considerably lower than the price P_B. Figure 17 clearly indicates that, in long run, the economy moves from point *A* to *C* on its long run supply curve (the bold and back curve of $\mathbf{S_L}$), not on the short run supply curve of S_A. From Figure 17, one can see that the short run supply curves of S_A and S_C are both less elastic than the long run supply curve of $\mathbf{S_L}$. In fact, the long run market mediated responses spread out the price impacts of ethanol production from one crop (i.e. corn) to all crops and by that they mitigate the price impacts for corn. As shown in tables 5 and 6, under all cases, production of corn ethanol affects supplies for all crop categories and their prices. Of course, the extent and intensity of changes vary by crop.

<Figure 17 Here>

We now explain the implications for food prices. Of course, changes in commodity prices do not translate directly to changes in food prices. When the ethanol RFS or both ethanol and biodiesel requirements were removed, the food price index fell by 0.04%. In other words, the RFS was responsible for only tiny changes in the overall food price index. When ethanol expansion was not permitted, the food price index dropped 0.21%, and when both ethanol and biodiesel expansion was prohibited, the drop was 0.25%. Biofuels did have some small impact on food prices, but not the RFS.

The other important factor to consider is changes in farm income. These are shown in Table 7 for the examined cases. First consider the impacts on farmers who produce crops. This row indicates removing ethanol mandates decreases incomes of farmers by $461.6 million and removing both mandates on corn ethanol and biodiesel lowers farmers' incomes by $1,299.6 million. These figures confirm that the RFS had positive impacts on farmer's incomes. Table 7 also indicates that removing the expansion in corn ethanol drops the farmers' incomes by $6,923.8 million. The drop in incomes increases to $8,010.6 million with no expansion of either ethanol or biodiesel. These figures confirm that biofuel production had significant favorable impacts on farmers' incomes during the first time period.

The last row of Table 7 shows the overall impacts on incomes of the agricultural sectors, including incomes of crop and livestock producers plus incomes of the forestry sector. This row shows slightly larger impacts (in absolute terms) compared with the first row. That confirms that agricultural activities in general gained form the RFS and also biofuel producers.

The additional farm incomes are attributed to two factors: 1) slightly higher crop prices induced by biofuel production and 2) retaining and allocating agricultural resources (say land) in higher valued activities. Compared to the baseline, with no expansion in biofuels, nearly 2,563 thousand hectares (6.3 million acres) of the US cropland would go out of production in the time period of 2004-11. The model assigns 16% of these areas to the RFS. In the absence of biofuel production and policy, agricultural production activities would have provided fewer employment opportunities resulted in idled agriculture production capacity and unused resources across rural areas

<Table 7 Here>

Results for 2011-16 time period

Conditions were quite different for the 2011-16 period than for the 2004-11 period. The earlier period was one of rapid growth in ethanol production driven primarily by increasing crude oil prices, the ethanol tax incentives, and changes in the use of ethanol as a source of oxygen and octane in blended fuels. The government's ethanol support ended in 2011. Ethanol's role in the gasoline fuel system as an important source of oxygen and octane had been established and continued through the second period and to today. In addition, in the second time period the price of crude oil declined sharply and that caused a sharp reduction in the price of conventional gasoline and a faster reduction in biofuel prices. These factors drove down profitability of ethanol production in the second time period significantly. On the other hand, the RFS targets for the first generation of biofuels (in particular for conventional ethanol) approached their higher required values.

Finally, it is important to take into account that the rate of ethanol blended with gasoline has increased rapidly from about 2.5% in 2004 to nearly 9.6% in 2011 and then continued to increase slowly to 10%. That suggests that in the second time period demand for ethanol basically continued to grow slowly to meet the adjusted down RFS quantities determined and set by the EPA, perhaps based on the traditional 10% maximum ethanol content. As mentioned before, in response to the observed high RIN prices, which could reflect constraints on the growth in consumption of ethanol, the EPA adjusted down the original enacted RFS targets for 2014-2016.

The effective mandated level of ethanol for 2016 was 14.3 BG[7]. When we remove this level of mandate, the market forces drop the consumption of ethanol to 12.5 BG. This means that the RFS on ethanol basically boosts consumption of ethanol by about 1.8 BG for the second time period. This means that the mandate on corn ethanol was more important in the second time period. In the PE section results, we will explain annual contributions of the RFS to consumption of ethanol. When we remove mandates on both ethanol and biodiesel, consumption of ethanol drops less (1.5 BG). That is because in the second case profitability increases in favor of corn ethanol.

We now analyze the impacts of RFS on commodity outputs and prices. First, we consider the impacts on commodity outputs presented in the first two numerical columns of Table 8. The first numerical column is for removing the ethanol mandate, and the second one is for removing both ethanol and biodiesel mandates. The results show if there was no mandate on ethanol, farmers would produce 2% less coarse grains (basically corn) and slightly more of other crops. This percent reduction in absolute terms is larger than the corresponding figure for the first time period. One needs to take into account the fact that the base of consumption in the second time period is also larger than the base of consumption in the first time period[8]. When we remove both mandates on ethanol and biodiesel, outputs of coarse grains drop by 1.6% and again supplies of other crops increase slightly.

Unlike the first time period, removing the expansion in corn ethanol alone (or jointly with biodiesel) has much smaller impacts on crop supplies. Compare the last two columns of Table 8 and with their corresponding columns of table 5. In the second time period, production of corn

[7] This was indeed very close to 10% of gasoline consumption in this year.
[8] Note that for the first time period, the comparison is for supplies of corn with and without mandate in 2011. For the second time period, the comparison is for supplies of corn with and without mandate in 2016.

ethanol did not grow substantially. It only changed from 13.9 BG in 2011 to 15.4 BG in 2016, an increase of 1.5 BG.

<Table 8 Here>

Regarding the commodity price impacts of RFS in the second time period, consider the first two numerical columns of Table 9. The first numerical column is for removing the ethanol mandate and the second one is for removing both ethanol and biodiesel mandates. Similar to the first time period, the results show that in the second time period the price impacts of removing the RFS requirements (for only corn ethanol or both biofuels) are small, less than 1%. Nonetheless, the RFS price impacts are larger in the second time period. Unlike the first time period, the RFS was the key driver of the expansion in biofuels in the second time period. Note that, unlike the first time period, removing the expansion in corn ethanol alone (or jointly with biodiesel) in the second time period has no large impacts on crop prices, compare the last two columns of tables 6 and 9. That is because, as mentioned before, in the second time period production of corn ethanol did not grow that much.

<Table 9 Here>

Finally, we present changes in farm incomes for the time period of 2011-16. Table 10 shows these changes. The first row of this table indicates that, for this time period, removing ethanol mandates drops incomes of farmers by $2,062.2 million, and removing both mandates on corn ethanol and biodiesel drops farmers' incomes by $2,454.8 million. These figures confirm that the RFS had positive and important impacts on farmer's incomes in 2011-2016. Table 10 also indicates that removing the expansion in corn ethanol drops the farmers' incomes by $1,652.2 million. The drop in incomes increases to $2,281.2 million with no expansion of either ethanol or biodiesel. These figures confirm that biofuel production had significant impacts on farmers' incomes during the second time period as well. The last row of Table 10 shows the overall impacts on incomes of agricultural sectors, including incomes of crop and livestock producers plus incomes of the forestry sector. This row shows slightly different impacts (in absolute terms) compared with the first row.

Compared to the baseline, with no expansion in biofuels, about 77 thousand hectares (160 thousand acres) of the US cropland would go out of production in the time period of 2011-16. The model assigns 100% of these areas to the RFS. Similar to the first time period, in the absence of biofuel production and policy, agricultural production activities would have provided fewer employment opportunities resulted in idled agriculture production capacity and unused resources across rural areas

<Table 10 Here>

Box 1. Long run analysis versus short-run analysis

In presenting the results for the first time period we explained why a large change in supply of corn in the long run induces a relatively moderate change in the corn price (see figure 17 and its corresponding analysis). We showed that the long run supply of corn is more elastic than its short run supply. That analysis applies to the second time period as well. For example, removing the ethanol mandate alone reduces supply of corn ethanol by 1.5 BG which causes a reduction in supply of coarse grains (basically corn) by 2%, and that leads to 0.9% reduction in the price. This represents a relatively elastic long run supply curve. Here we show that in the short run when demand and supply functions operate with lower elasticities, and markets have limited capacities to respond to the economic shocks, the price impacts could be larger.

To depict the short run impacts, we repeated the experiment that drops the mandates for ethanol and biodiesel with an inelastic supply for corn, lower substitution between corn and DDGs, and a lower trade elasticity for corn. With these short term elasticities, the drop in the price of coarse grains changed from -0.9% to -6.7%. We then kept the low trade elasticity and the low substitution between corn and DDGS and allowed the supply of corn to respond. In this case the price of corn changed by -2.7%.

Partial equilibrium model results

The partial equilibrium model described above (AEPE) was used to simulate the annual changes from 2005 to 2016. The model was calibrated to 2005. For the simulations, corn and soybean yields were targeted as in the CGE model. Total area of corn and soybeans (not individually) was also targeted. So, the model allocates land between corn and soybeans. Throughout the period, crude oil price was exogenous as explained above. The net trade of ethanol is exogenous in the PE model. The gasoline consumption was tuned to actual values via shifters. By using demand shifters, we attempted to capture drivers like the 2006 MTBE substitution and the later use of ethanol as an octane additive for blended gasoline. Of course, we also captured the 2012 drought and other agricultural commodity supply and demand changes due to changes in world market conditions. Following the CGE approach, we first developed a historical baseline. However, unlike the CGE work, the PE baseline covers annual changes for each year from 2005 to 2016. Then we made market based annual simulations that only take into account market forces to determine production and consumption of ethanol. Finally, it is important to note that, unlike the CGE model, the PE model uses nominal prices. Hence, the prices presented below are nominal values.

In what follows we present the results for the market based simulations and compare them with actual observations. We begin with consumption of ethanol. The actual observations and simulated market based results for ethanol consumption are presented in Figure 18. This figure indicates that prior to 2011 the market based projections for ethanol consumption were usually slightly larger than their real world observations, with one exception in 2008. That suggests a binding RFS in this year. Since 2011 the market based projections for ethanol consumption were smaller than their real world observations. That means the RFS pushed up consumption of ethanol in these years. For example, in 2016 the actual consumption of ethanol was 14.3 BG with a market based projection of 12.1 BG. This means that in this particular year the RFS increased consumption of ethanol by about 2.1 BG. This is the largest contribution of RFS to ethanol consumption over our study period. These results are consistent with our CGE findings.

<Figure 18 Here>

The actual observations and simulated market based results for corn and soybean prices are presented in Figure 19. This figure shows that, in general, the actual observations and market based projections are similar with some noticeable exceptions. For example, in 2016 the actual corn price was $3.33 per bushel with a market based projection of $3.16 per bushel, 5% lower than the actual observation. From 2005 to 2009 the market based projections for the price of corn were higher than the baseline, and then the reverse occurred.

<Figure 19 Here>

The actual observations and simulated market based results for ethanol and gasoline prices are presented in Figure 20. This figure shows that, from 2005 to 2010 the market based projections for ethanol price are higher than the actual observations, except in 2008. Then from 2011 the reverse has happened. For example, the actual ethanol price in 2016 was $1.43 per gallon with a market based projection of $1.20 per gallon. Hence one can conclude that since 2011 the RFS has positively affected the price of ethanol.

<Figure 20 Here>

5. Conclusions

The relationship between the U.S. Renewable Fuel Standard (RFS) and commodity and food prices is very complicated. Part of the complication is the question of attribution. Some of the early literature tended to blame the RFS for all increases in commodity prices. However, over time it has become abundantly clear that many factors have been involved in the evolution of commodity and food prices, with the RFS and biofuel production in general being only one. The purpose of this study is to determine the extent to which commodity and food prices were driven by the RFS and to what extent they were driven by biofuels regardless of what caused the level of biofuels production.

This study first examines the literature and data on what was actually happening in agricultural and energy markets over the relevant period. From the data presentation and literature review alone, it became clear that the bulk of the ethanol production prior to 2012 was driven by what was happening in the national and global markets for energy and agricultural commodities and by the federal and sometimes state incentives for biofuel production. This conclusion is supported by examining the data, by the conclusions of the recent literature, and by the fact that until 2012 the RINs prices were very low, indicating that the non-RFS policies and market forces (demand for ethanol as a fuel extender, demand for ethanol as an additive, and MTBE ban) helped biofuels to grow, while the RFS provided a safety net for the whole biofuel industry to invest and expand its production capacity by requiring minimum levels of biofuels use.

We provided long run CGE analyses for two time periods: 2004-2011 and 2011-2016. Our results confirm that, in general, the long run price impacts of biofuel production were not large. Due to biofuel production, regardless of the drivers, crop prices (adjusted to inflation) have increased between 1.1% (for wheat) and 5.5% (for the category of coarse grains) in the first time period (i.e. 2004-11). The model determines the contributions of RFS to the price increases due to biofuel production. For example, it assigns only one-tenth of the 5.5% increase in the price of coarse grains to the RFS. For the second time period (i.e. 2011-16) the long run price impacts of biofuels were less than the first time period, as in this period biofuel production has increased slowly. Due to biofuel production, crop prices have increased by less than 1% in the second time period. However, unlike the first time period, the RFS was the main driver of these changes. Finally, in both time periods, the long run effects of biofuel production and policy on food prices were negligible for both time periods.

The long run CGE results indicate that biofuel production and policy made major contributions to the agricultural sector in both time periods, while they only affected the commodity prices moderately. Biofuel production, regardless of the drivers, has increased the US annual farm incomes by $8.3 billion and $2.3 billion at constant prices in the first and second time periods, respectively. Hence, with no biofuels, the US annual farm income would drop by an estimated $10.6 billion, ignoring the changes since 2016. The model assigns 28% the expansion in farm incomes of the first time period to the RFS. The corresponding figure for the second time period is 100%. This means that, the additional gains in farm incomes were entirely due to the RFS in the second time period.

The PE analyses indicate that prior to 2011 the market based projections for annual consumption of ethanol are usually smaller than their real world observations, with one exception in 2008. That suggests a binding RFS in this year. Since 2011 the market based projections for annual ethanol consumption are smaller than their real world observations. That means the RFS pushed up consumption of ethanol in these years. The RFS has increased the demand for ethanol by 7% to 14% between 2011 and 2016. For example, in 2016 the actual consumption of ethanol was 14.3 BG with a market based projection of 12.1 BG. This means that in this particular year the RFS increased consumption of ethanol by about 2.1 BG. The impact of RFS on the price of corn in this year was about 5%.

Prior to 2011, ethanol was basically in demand as a fuel extender and an octane additive. This has changed after this year and a portion of ethanol was consumed as a source of octane and as a substitute for gasoline to meet the RFS requirements. Since 2011 as the total consumption of ethanol moved towards the historical 10% maximum ethanol content (that was allowed in non-flex-fuel vehicles), demand for gasoline, and hence, ethanol did not grow enough and that raised the RINs prices. This could change in the future considering that E15 has been approved for use in 2001 and newer vehicles since 2011 and flex-fuel vehicles using E85. The USDA's 2015 Biofuels Infrastructure Partnership, in combination with private-sector resources, has helped improve market access for higher blends of ethanol. The more recent evidence confirms that the consumption of ethanol has passed the historical 10% bend rate and demand for E15 and E85 is growing since 2016. Since our analyses end in 2016, this paper does not cover these new developments.

There is clearly a difference in impacts of the RFS and biofuels production due to market forces. One of the main contributions of this research is to demonstrate that biofuels production growth that is often attributed to the RFS is actually due to energy and agricultural market conditions and key drivers. We have identified and characterized these drivers and shown that the market drivers have been the main contributor to biofuels growth, in particular through 2011. In a sense, this means that biofuels' contribution to commodity price increases is really no different from fructose corn syrup, increased feed demands, or other market demands. To understand what has happened to agricultural markets over the past two decades, it is absolutely critical to include in the analysis all the global and national demand and supply factors in both energy and agricultural markets, and we have done that.

An interesting question to ask given our conclusions on the role of markets in driving biofuels growth is how it would have been different if all these market changes had not occurred. In other words, what if crude oil price had not surged, MTBE had not been banned, ethanol did not get integrated into the fuel system becoming a fuel additive instead of a fuel extender, etc.? The answer is clearly that the RFS would have played a much greater role. So, in a sense, the RFS has been the backstop, but by circumstance, it was overpowered by tax incentives and market forces prior to 2011.

Another interesting comparison is between what happened over this period for ethanol compared with biodiesel and cellulosic biofuels. For both biodiesel and cellulosic biofuels, the RFS was clearly an important driver of production and consumption. RIN prices were always relatively high, and the RFS was always binding. Clearly, the market changes that benefitted ethanol did not work as much in favor of these other biofuels.

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Table 1. Periods used for this analysis

Period	Key descriptors and drivers
1980-2004	Early ethanol years; low oil prices; ethanol tax exemption or tax credit
2004-2008	Rapid increase in crude oil prices; RFS; continuation of tax credits or incentives; MTBE ban in 2006; food/fuel issues in 2008
2008-2009	Great recession
2010-2011	Commodity prices increased again due to a variety of drivers; ethanol became an even more important source of octane in gasoline blends
2011-2016	Ethanol government support ended; RFS became binding; Moving towards the historical perception of the blend wall: 10% maximum ethanol content

Table 2. Adjusted RFS, blended gasoline consumption, calculated pure gasoline, and calculated ethanol (BG)

Year	Adjusted RFS by EPA	Actual total gasoline blended	Calculated pure gasoline	Calculated ethanol blended at a 10% rate
2013	13.8	135.56	122.01	13.56
2014	13.61	136.76	123.08	13.68
2015	14.05	140.70	126.63	14.07
2016	14.5	143.22	128.90	14.32

Source: Authors' calculations with the total blended gasoline data from EIA. The effect of small refinery exemptions on the net RFS during any of these years is not included.

Table 3. Percent Changes in macro variables for 2004-11 and 2011-16

Description	US		Rest of the world	
	2004-11	2011-16	2004-11	2011-16
% Change in real GDP	9.1	11.1	25.8	14.8
% Changes in gross investment	-8.2	19.6	41.2	15.9
% Change population	6.4	3.7	9.1	6.2
% Change in labor force	4.6	3.5	8.9	6.4

Source: Authors' calculations based on data obtained for the World Bank data set

Table 4. Crop production and harvested area 2004, 2011 and 2016

Description		2004		2011		2016	
		US	Rest of the world	US	Rest of the world	US	Rest of the world
Production in million metric tons	Coarse grains	308	673	319	790	392	903
	Soybeans	85	121	84	178	117	219
	Other crops	928	7074	887	8326	908	8956
Area in million hectares	Coarse grains	33	237	36	245	37	257
	Soybeans	30	62	30	74	33	88
	Other crops	65	938	60	1014	64	1044

Sources: Data obtained from GTAP data base and FAO

Table 5. Percentage change in crop outputs under alternative examined counterfactual experiments for 2004-2011

Description	Removing mandate of corn ethanol	Removing mandates of corn ethanol & biodiesel	No expansion in corn ethanol	No expansion in biofuels
Coarse grains	-1.2	-1.4	-20.8	-20.8
Soybeans	0.2	-1.6	3.2	0.1
Wheat	0.1	0.6	2.4	3.0
Rice	0.0	0.2	0.7	1.0
Sorghum	0.0	0.0	0.6	0.6
Rapeseed	0.2	-12.4*	5.6	-11.0*
Other oilseeds	0.1	-4.3	1.8	-3.6
Sugar crops	0.0	0.1	0.4	0.4
Other crops	0.1	0.0	1.0	0.8

* Large percentage changes for rapeseed are due to very small quantities in the base year.

Table 6. Percentage change in real commodity prices under alternative counterfactual experiments for 2004-2011

Description	Removing mandate of corn ethanol	Removing mandates of corn ethanol & biodiesel	No expansion in corn ethanol	No expansion in biofuels
Coarse grains	-0.3	-0.6	-5.3	-5.5
Soybeans	-0.1	-0.7	-1.6	-2.5
Wheat	-0.1	-0.2	-0.9	-1.1
Rice	-0.1	-0.2	-1.0	-1.2
Sorghum	-0.1	-0.2	-0.9	-1.1
Rapeseed	-0.1	-3.2	-1.3	-5.0
Other oilseeds	-0.1	-0.8	-0.9	-1.8
Sugar crops	-0.2	-0.5	-3.6	-4.0
Other crops	-0.1	-0.4	-1.7	-2.0

Table 7. Changes in farm income with and without the RFS and biofuel changes for 2004-2011 (Million USD)

Description	Removing mandate of corn ethanol	Removing mandates of corn ethanol & biodiesel	No expansion in corn ethanol	No expansion in biofuels
Crop sectors	-461.6	-1,299.6	-6,923.8	-8,010.6
Overall agriculture	-478.9	-1,371.0	-7,143.3	-8,313.1

Table 8. Percentage change in crop outputs under alternative examined counterfactual experiments for 2011-2016

Description	Removing mandate of corn ethanol	Removing mandates of corn ethanol & biodiesel	No expansion in corn ethanol	No expansion in biofuels
Coarse grains	-2.0	-1.6	-1.6	-1.6
Soybeans	1.1	0.3	0.9	0.5
Wheat	0.8	0.4	0.6	0.3
Rice	1.1	1.2	0.9	1.1
Sorghum	0.0	0.5	0.0	0.4
Rapeseed	1.9	1.5	1.5	1.6
Other oilseeds	1.0	0.5	0.8	0.7
Sugar crops	0.6	0.5	0.6	0.6
Other crops	0.4	0.3	0.3	0.3

Table 9. Percentage change in real commodity prices under alternative counterfactual experiments for 2011-2016

Description	Removing mandate of corn ethanol	Removing mandates of corn ethanol & biodiesel	No expansion in corn ethanol	No expansion in biofuels
Coarse grains	-0.9	-0.9	-0.7	-0.8
Soybeans	-0.3	-0.5	-0.2	-0.4
Wheat	-0.1	-0.1	-0.1	-0.1
Rice	-0.2	-0.3	-0.2	-0.3
Sorghum	-0.6	-0.6	-0.4	-0.5
Rapeseed	-0.2	-0.5	-0.2	-0.4
Other oilseeds	-0.2	-0.5	-0.2	-0.3
Sugar crops	-0.7	-0.8	-0.5	-0.7
Other crops	-0.3	-0.4	-0.3	-0.3

Table 10. Changes in farm income with and without the RFS and biofuel changes for 2011-16 (Million USD)

Description	Removing mandate of corn ethanol	Removing mandates of corn ethanol & biodiesel	No expansion in corn ethanol	No expansion in biofuels
Crop sectors	-2,062.2	-2,454.8	-1,652.2	-2,281.2
Overall agriculture	-2,040.6	-2,414.2	-1,635.9	-2,222.6

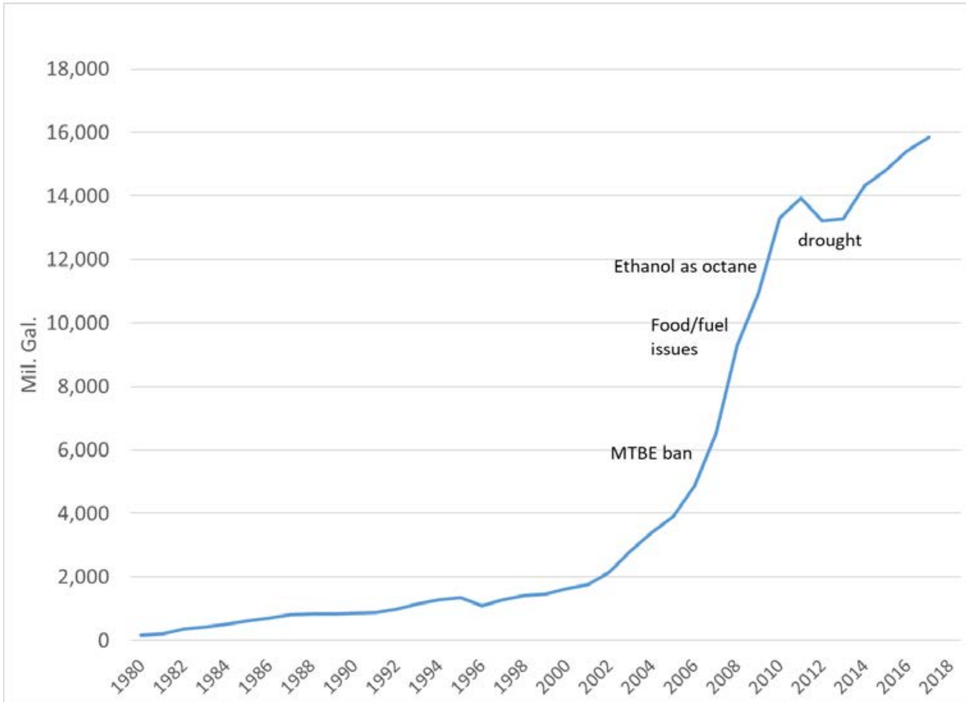


Figure 1. Annual Ethanol Production

Source: Figure authors with data from the Renewable Fuels Association [9]

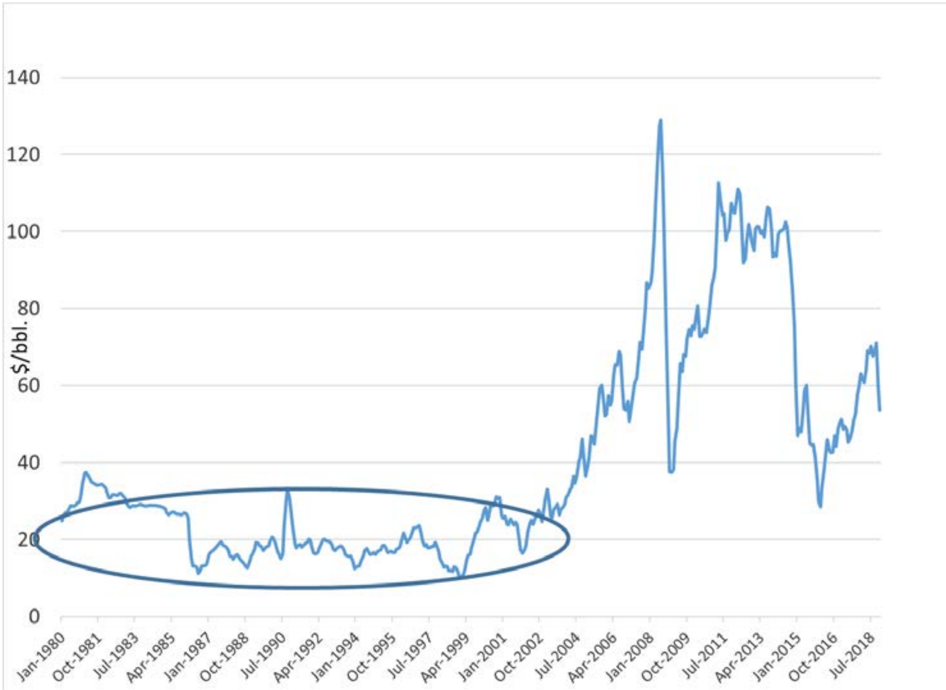


Figure 2. Crude Oil Composite Acquisition Cost

Source: Data from the US Energy Information Administration [11]

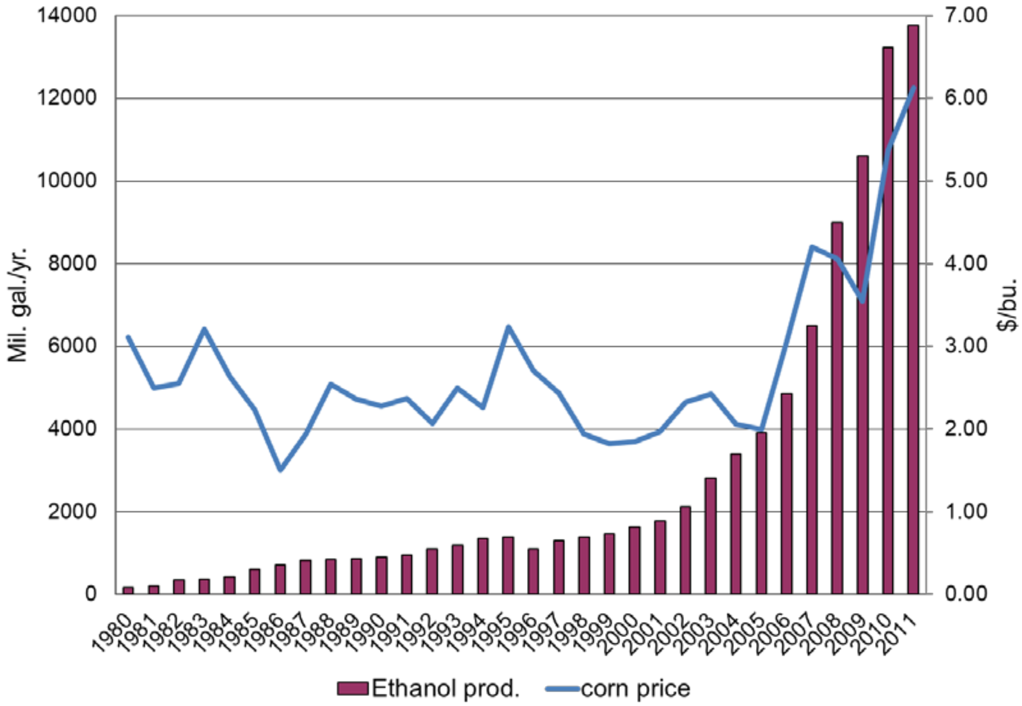


Figure 3. Ethanol Production and Average Annual Corn Price (1980-2011)

Source: [3], original data from RFS and USDA

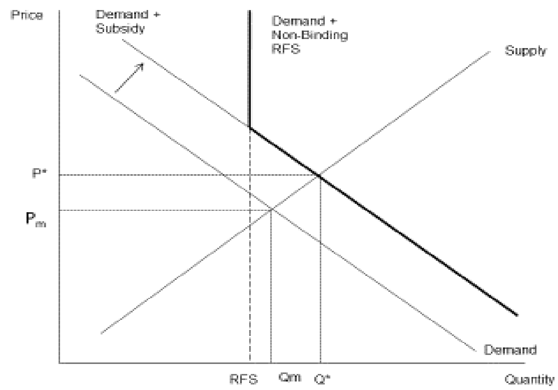


Figure 4. Non-binding RFS level

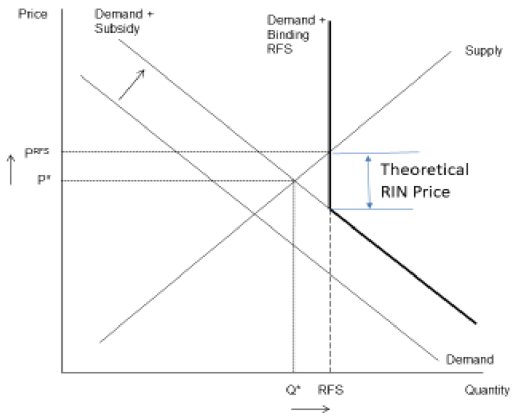


Figure 5. Binding RFS

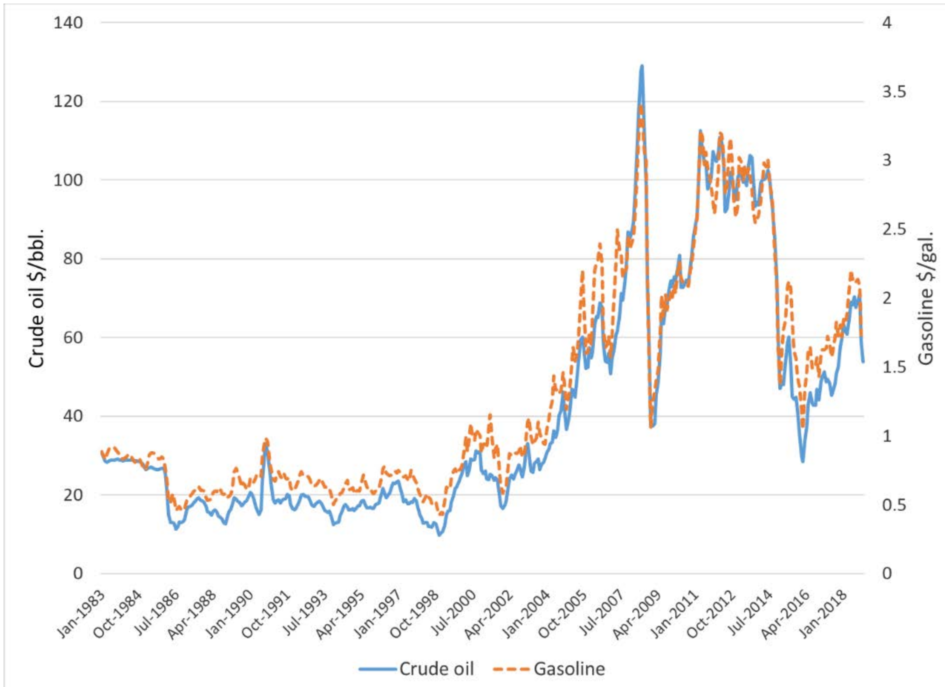


Figure 6. Crude Oil Composite Acquisition Cost and Wholesale Gasoline Prices

Data Source: US Department of Energy [11, 15]

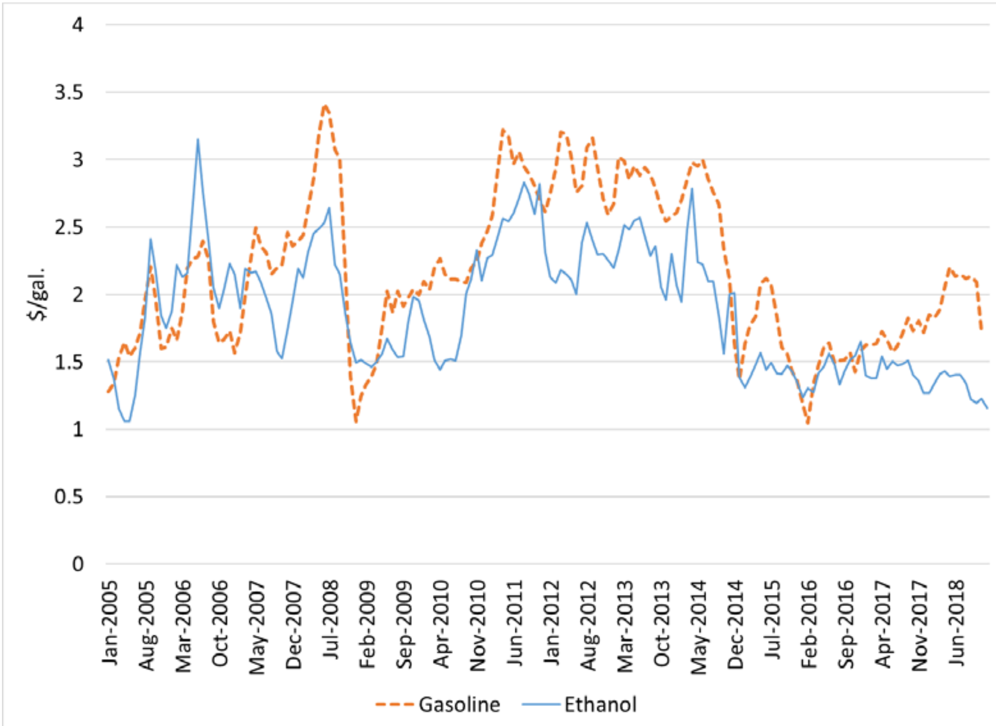


Figure 7. Gasoline and Ethanol Prices

Source: Iowa State Agricultural Marketing Resource Center [16]

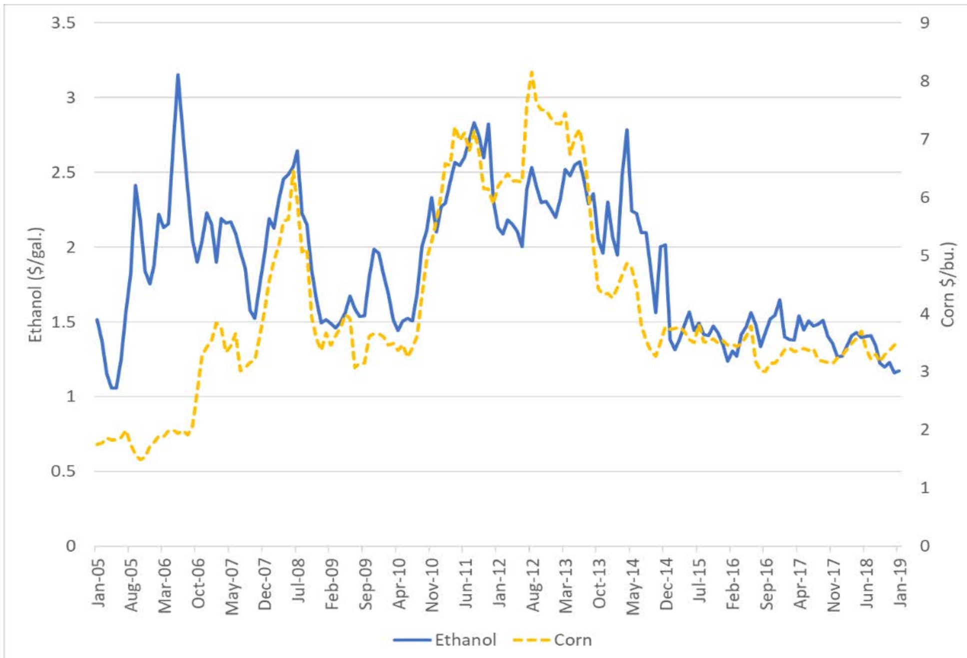


Figure 8. Ethanol and Corn Prices

Source: Iowa State Agricultural Marketing Resource Center [16]

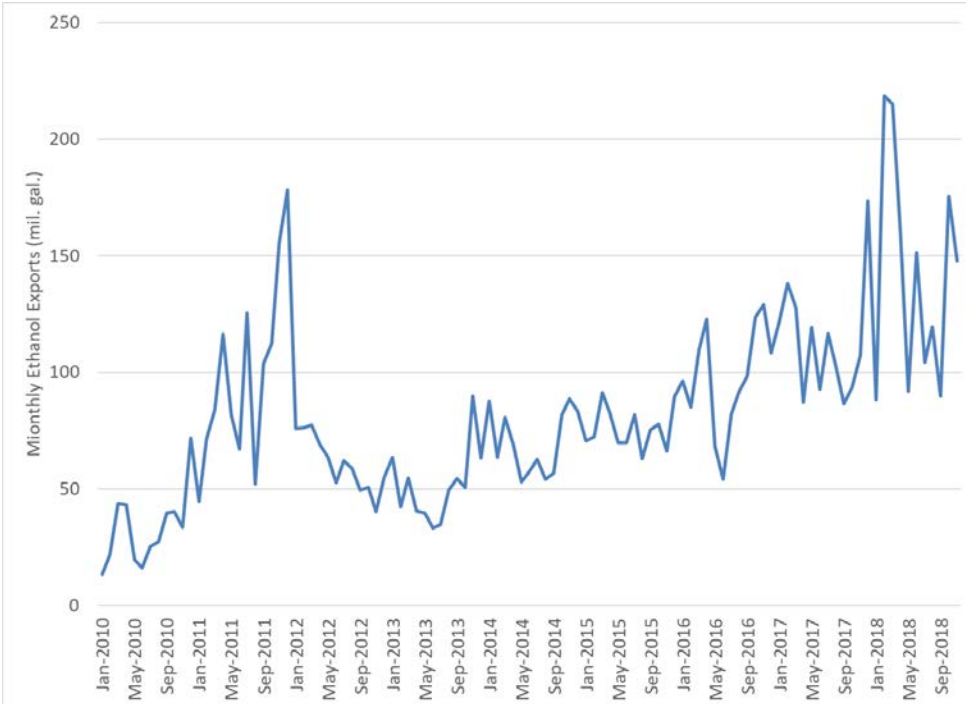


Figure 9. Monthly Ethanol Exports (2010-2018)

Source: Renewable Fuels Association [9]

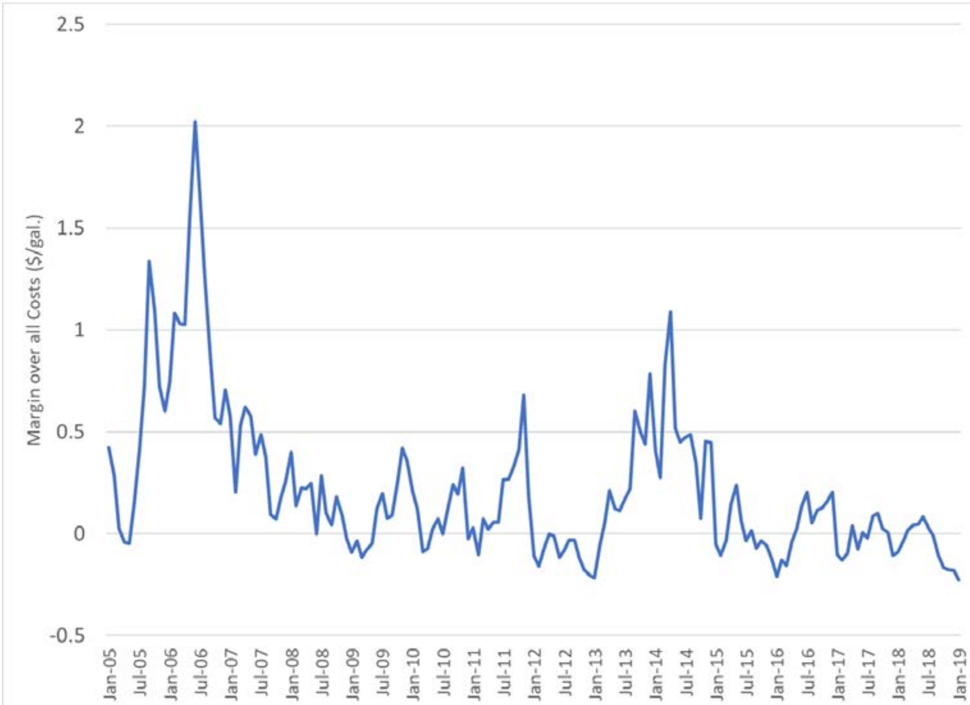


Figure 10. Ethanol Profitability Margins

Source:[16]

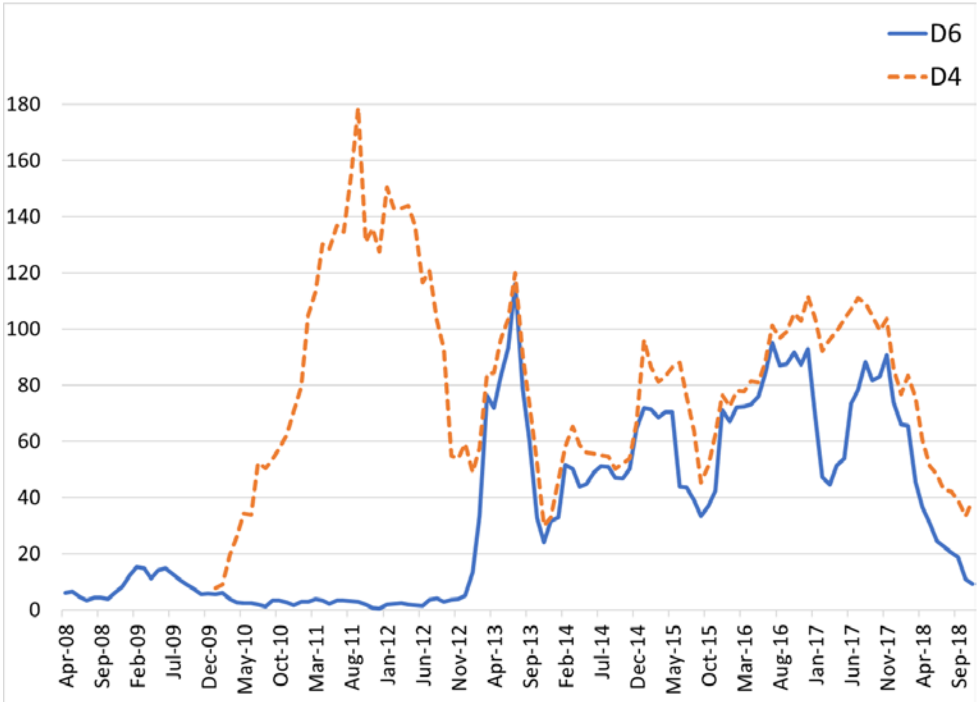


Figure 11. Monthly Average D6 (ethanol) and D4 (Biodiesel) RIN Prices

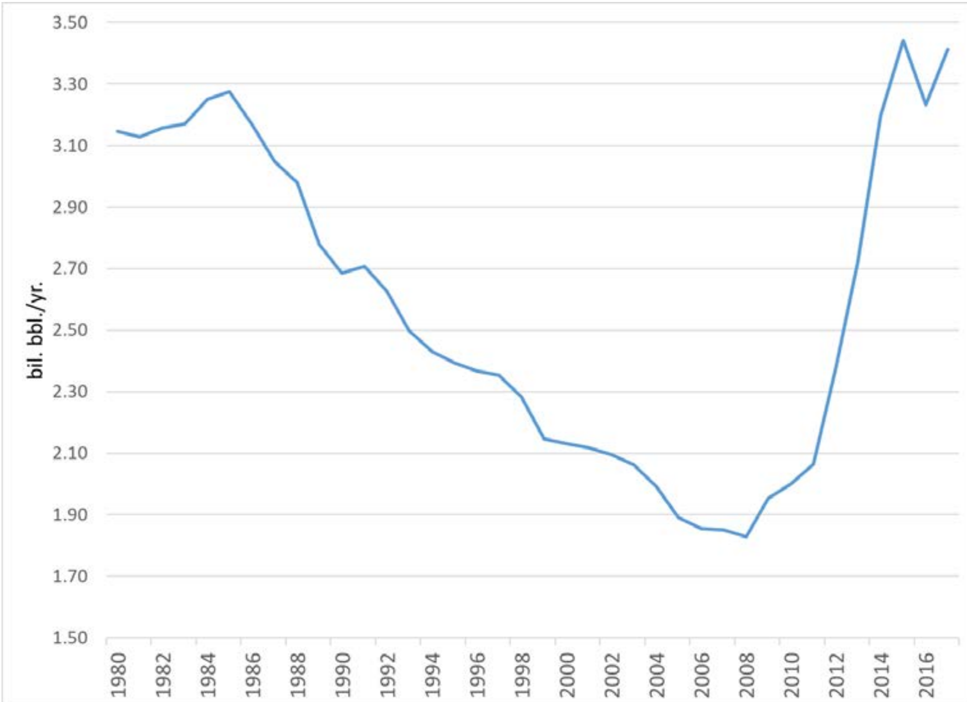


Figure 12. US Annual Crude Oil Production (1980-2017)

Source: Energy Information Administration [29]

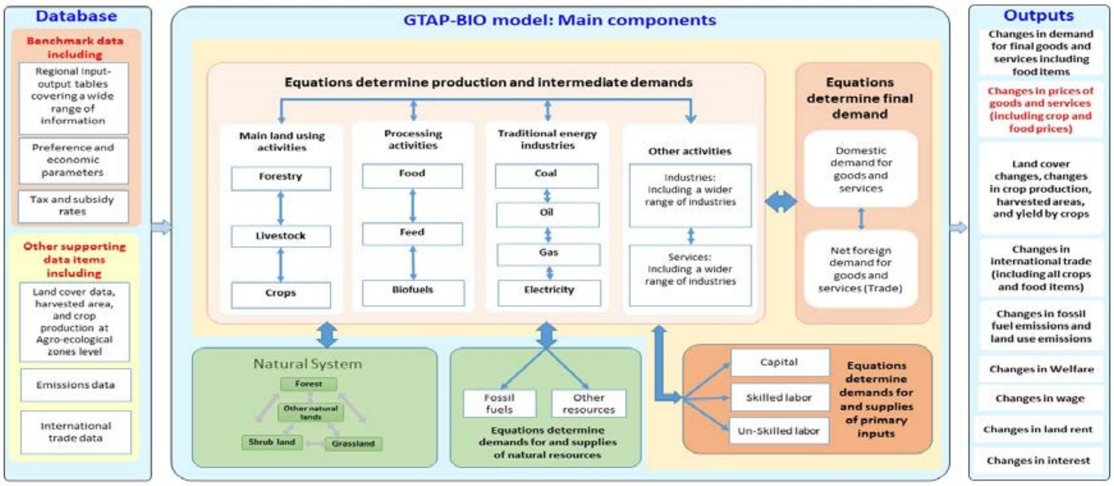


Figure 13. Structure of GTAP-BIO model

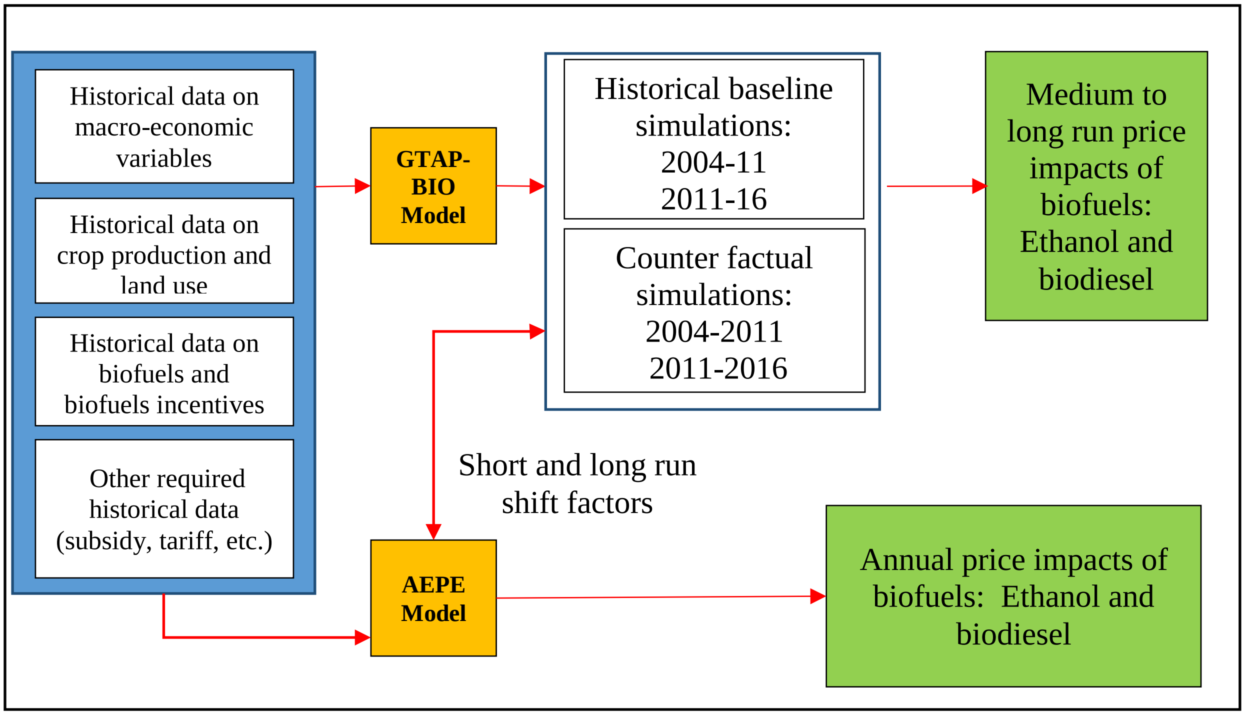


Figure 14. The overall modeling approach

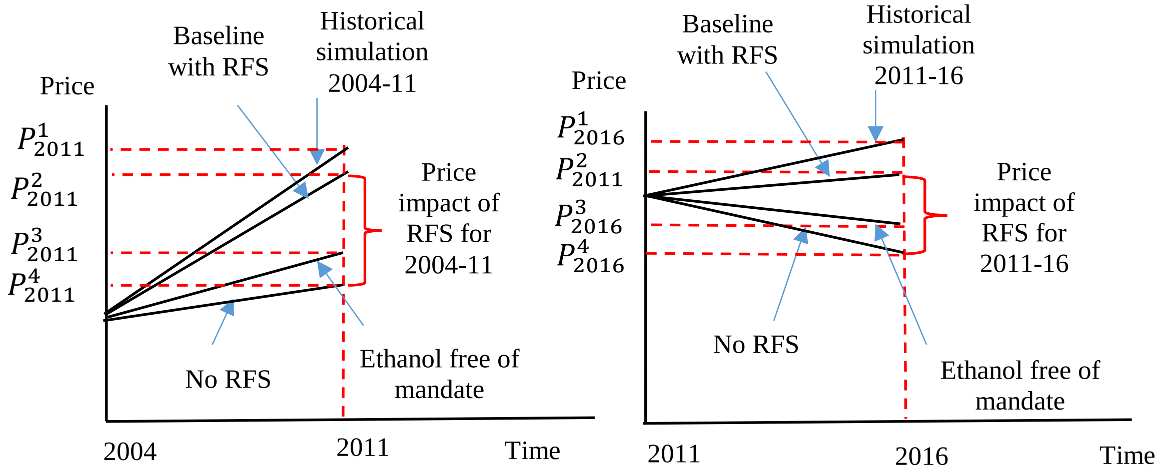


Figure 15a. A schematic representation of historical baselines and counterfactual experiments including: *Baselines with RFS*, *Ethanol free of mandate*, and *no RFS*.

The left panel represents 2004-11 and the right panel 2011-16. The vertical axis shows the price of a representative product. P^1, P^2, P^3, and P^4 indicate the projected prices of this product for the *historical baselines*, *Baseline with RFS*, *Ethanol free of mandate*, and *No RFS* experiments, respectively.

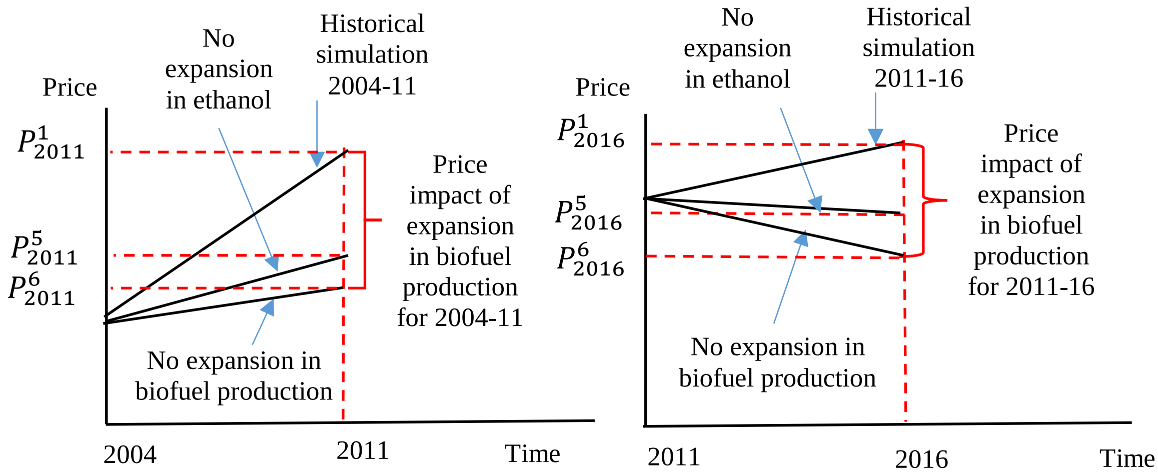
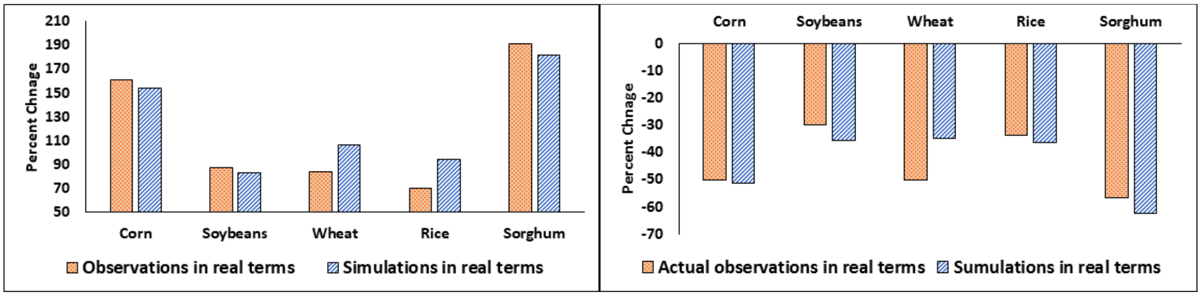


Figure 15b. A schematic representation of historical baselines and counterfactual experiments including: *No expansion in ethanol* and *No expansion in biofuels*.

The left panel represents 2004-11 and the right panel illustrates 2011-16. The vertical axis shows the price of a representative product. P^1, P^5, and P^6 show the projected prices of this product for the *historical baselines*, *No expansion in ethanol* and *No expansion* in biofuels, respectively.



2004-11 2011-2016

Figure 16. Observed and simulated percent change in real crop prices for time periods of 2004-11 (left panel) and 2011-16 (right panel)

The GDP price deflator is used to convert nominal prices to real prices.

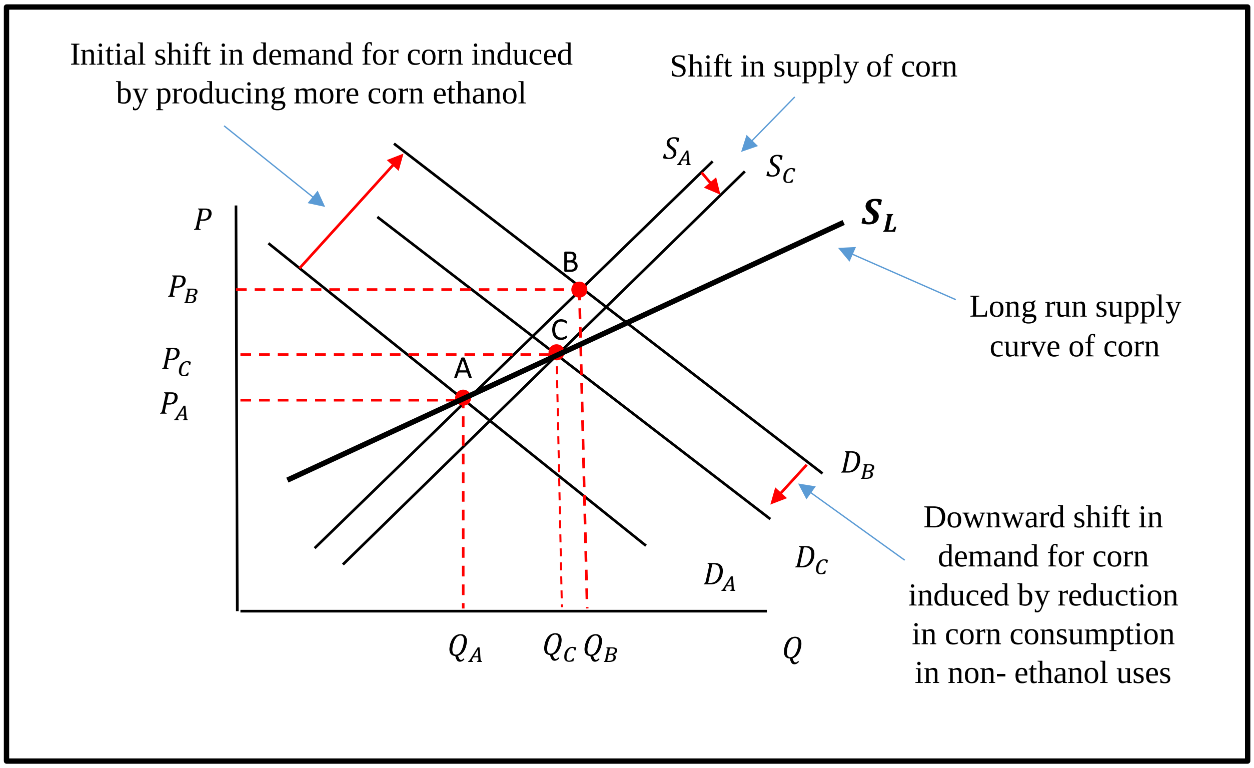


Figure 17. Short run and long run changes in corn market

This figure was designed to explain difference between the short and long run supply elasticities. The demand and supply curves and their shifts are all hypothetical. Box 1 shows numerical estimates.

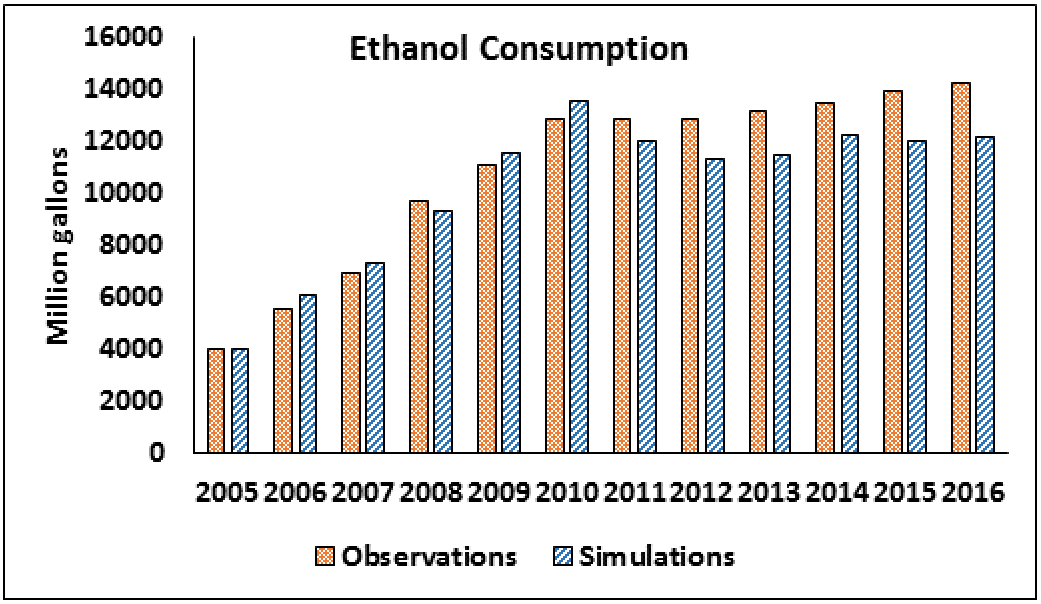


Figure 18. Actual and simulated market results for ethanol consumption 2005-16

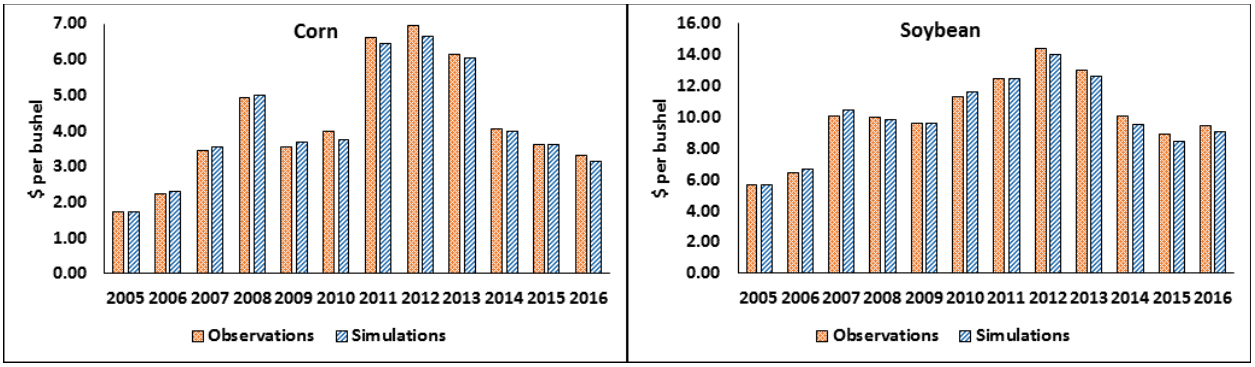


Figure 19. Observed and simulated market results for corn and soybean nominal prices 2005-16

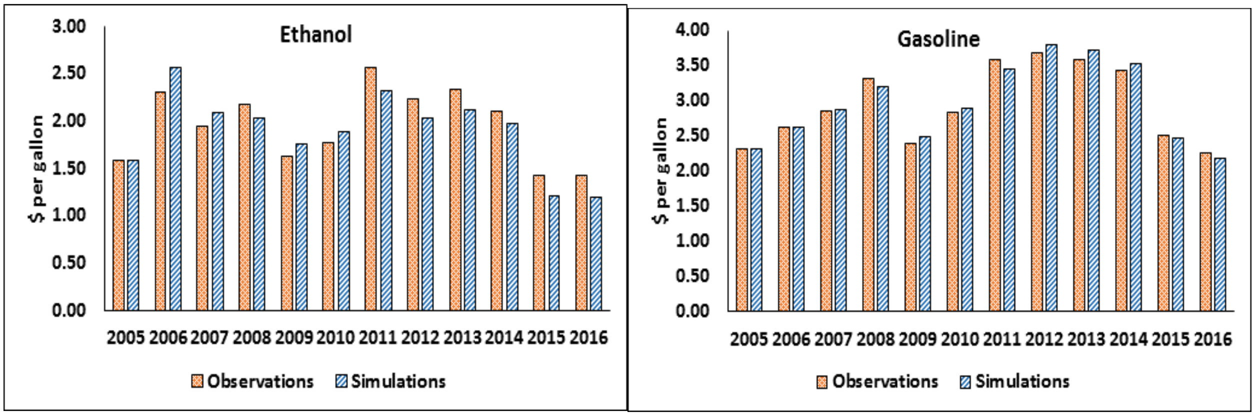


Figure 20. Observed and simulated market results for ethanol and gasoline nominal prices 2005-16