Supplementary Material

1 Background, Literature Review, and Data Analysis

Determining the economic impacts of the U.S. Renewable Fuel Standard (RFS) is a complicated task. 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 (U.S. Congress, 2005). The RFS was amended in 2007, and the revised and current RFS is sometimes referred to as RFS2 (U.S. Congress, 2007). 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 (Tyner, 2012). However, prior to the enactment of the RFS, there was other legislation related to ethanol, which is summarized by Tyner (2008). The National Energy Conservation Policy Act (U.S. Congress, 1978) 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 (U.S. Congress, 2004). 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.

The literature review and data analysis provided in this Supplementary Material (SM) are divided into five periods that are characterized by different drivers (Table S1). 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 (U.S. Congress, 1990).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 (2014). We also will cover other important papers that examine the time varying relationship between biofuels and

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

commodity and food prices. The literature review concludes with a summary of key points to be considered in the analysis that follows.

Table S1 | 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

Figure S1 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.

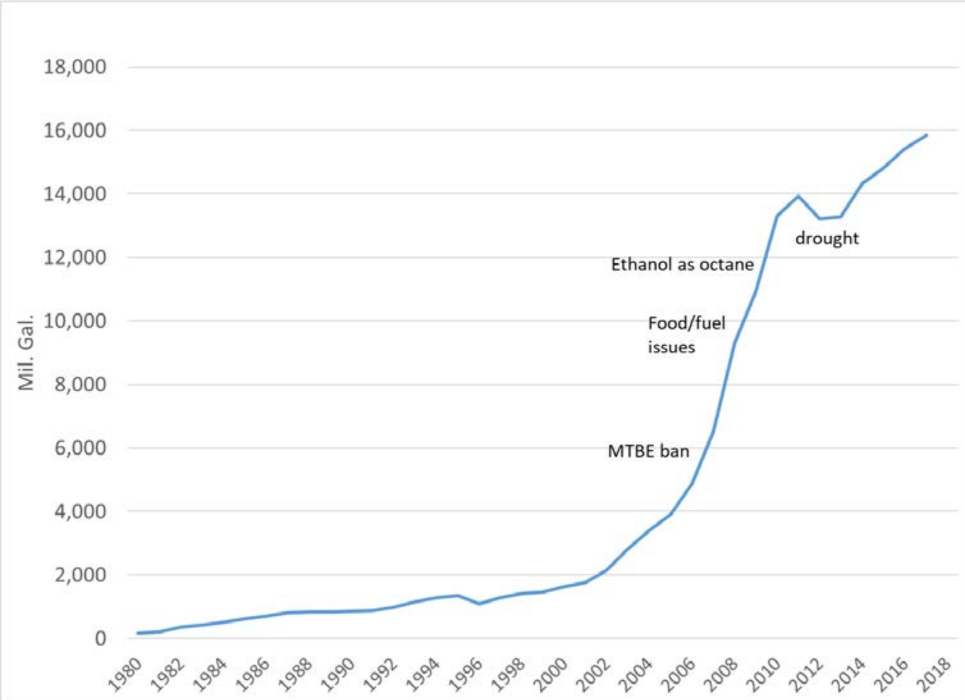

Figure S1 | Annual Ethanol Production:

Source: Figure authors with data from Renewable Fuels Association (2019)

1.1 Prior to 2004

Figure S2 shows monthly crude oil prices for the period 1980 to present. The time period identified by the oval in Figure S2 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 (Tyner, 2008). 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 S3). 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 (Tyner, 2008; Hertel et al., 2010). 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.

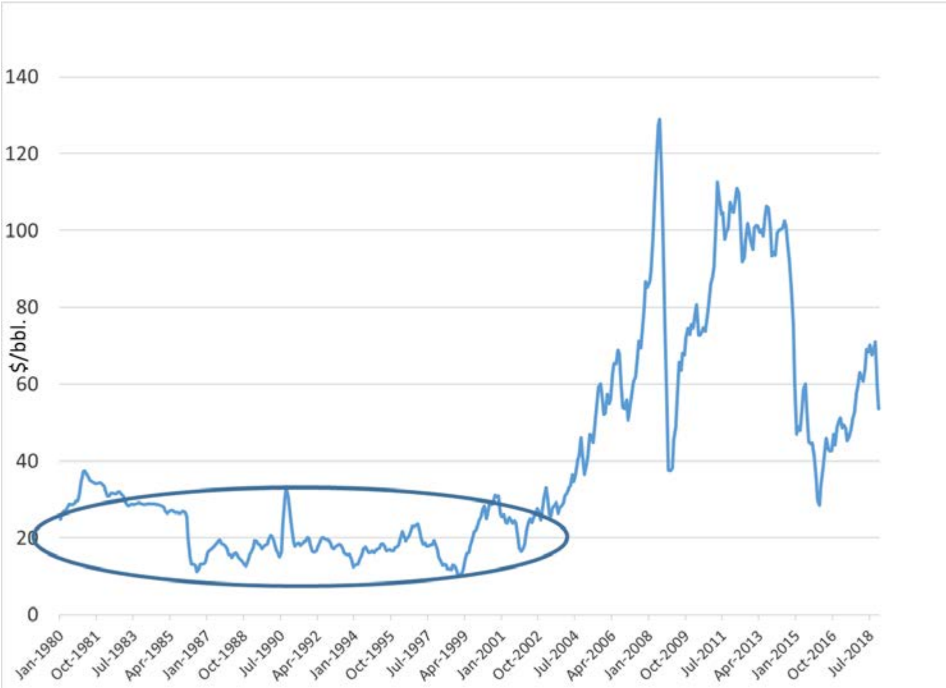

Figure S2 | Crude Oil Composite Acquisition Cost

Source: Data from U.S. Energy Information Administration (2019a)

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 (Tyner, 2010). There was no significant correlation between crude oil and the corn price during this early period. This lack of relationship is illustrated in Figure S3. 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.

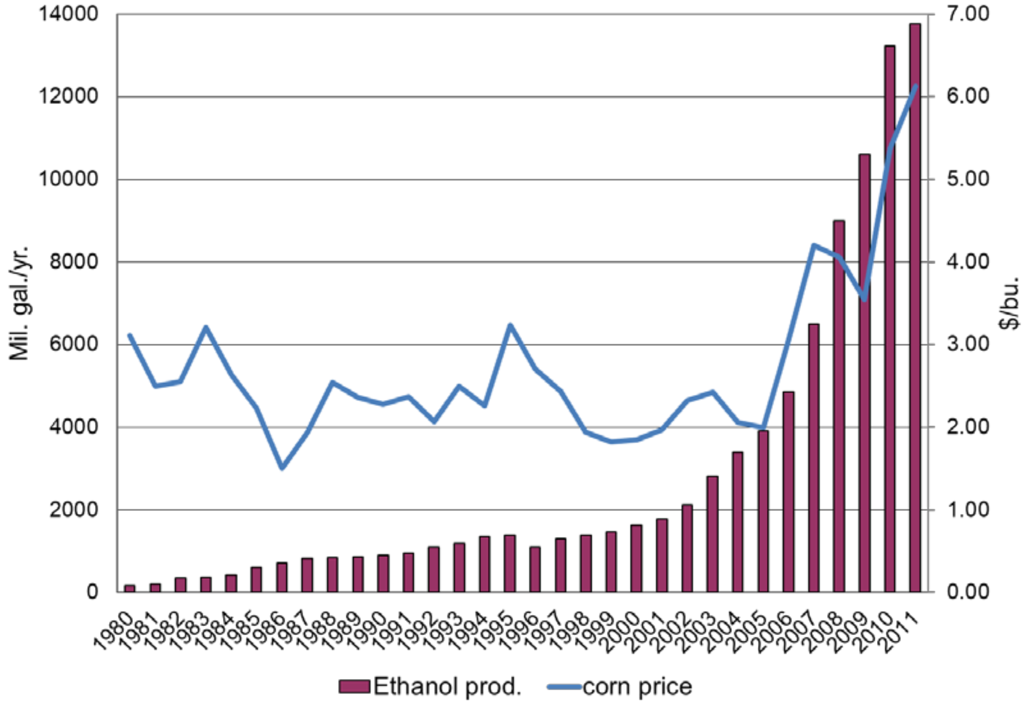

Figure S3 | Ethanol Production and Average Annual Corn Price (1980-2011)

Source: (Tyner, 2012), original data from RFS and USDA

1.2 2004-2008

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 S4 and S5 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 S5. 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 S4), RIN prices are quite low, and essentially represent transactions costs among industry players (Abbott, 2014) 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.

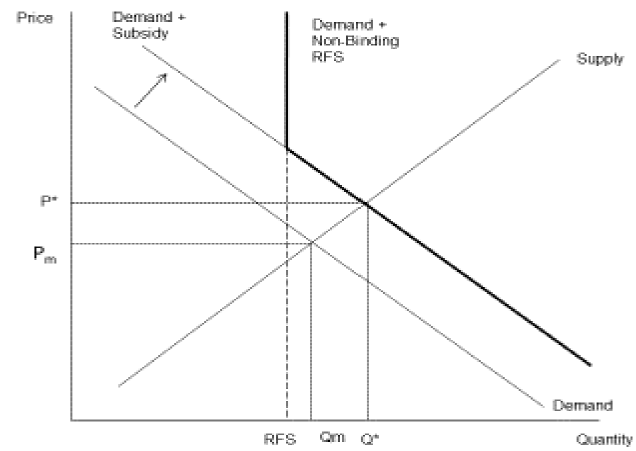

Figure S4 | Non-binding RFS level

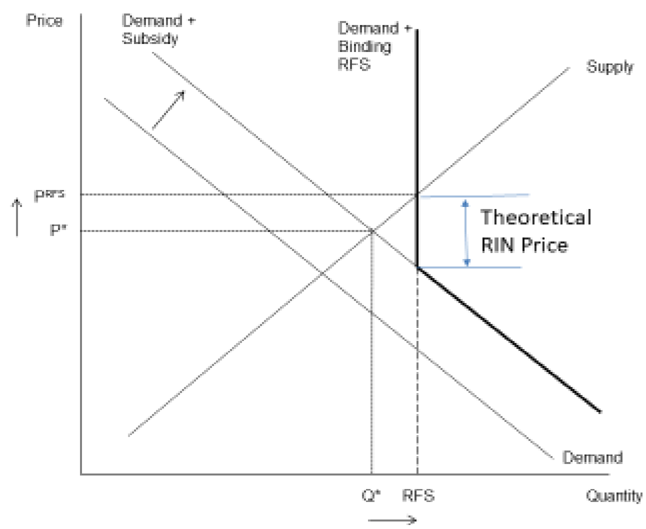

Figure S5 | Binding RFS

The first big pull was the rapid escalation in crude oil and gasoline prices. These prices are illustrated in Figure S6, 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 S7) and made investment in ethanol more attractive.

Another key driver easily visible in Figure S7 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 U.S. Energy Information Administration (EIA), ethanol blended at a 5.8% rate could provide the needed oxygen (U.S. Energy Information Administration, 2000) . 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 S8).

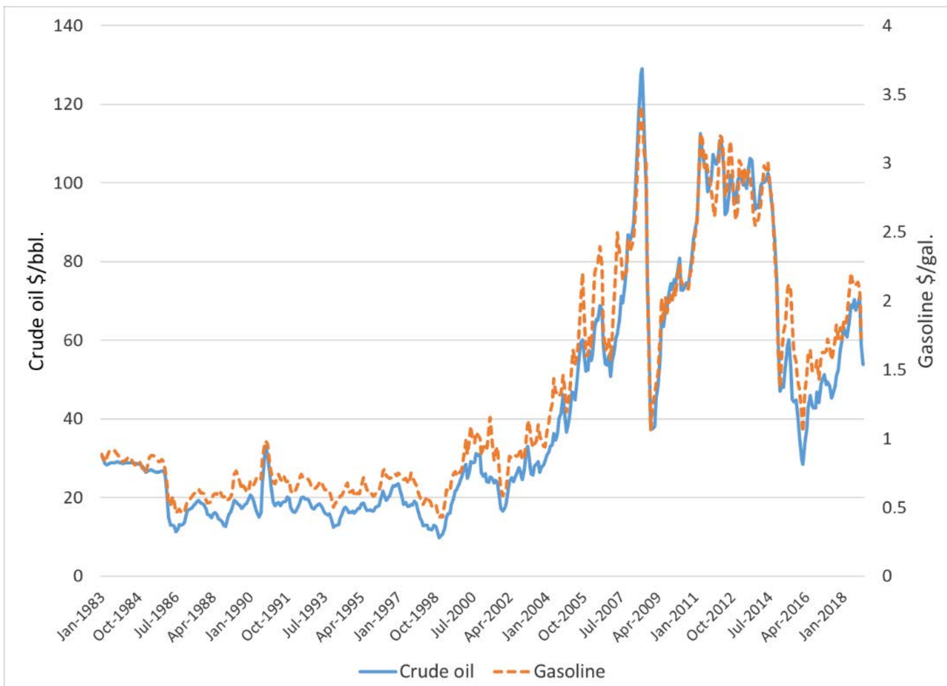

Figure S6 | Crude Oil Composite Acquisition Cost and Wholesale Gasoline Prices

Data Source: U. S. Energy Information Administration (2019a) (2019b)

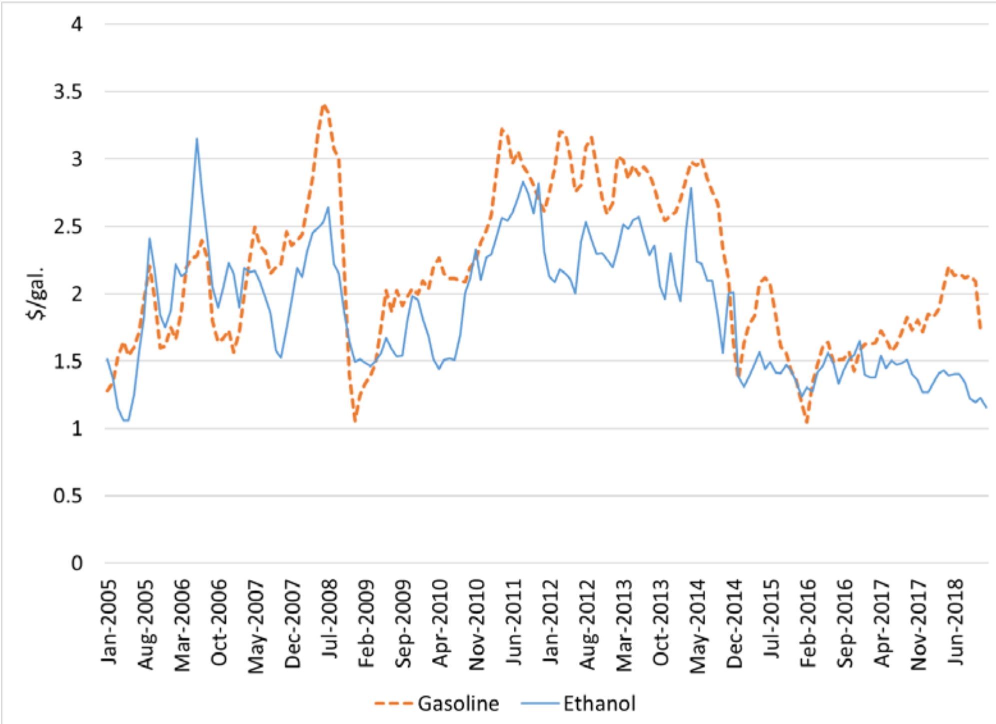

Figure S7 | Gasoline and Ethanol Prices

Source: Iowa State Agricultural Marketing Resource (2019)

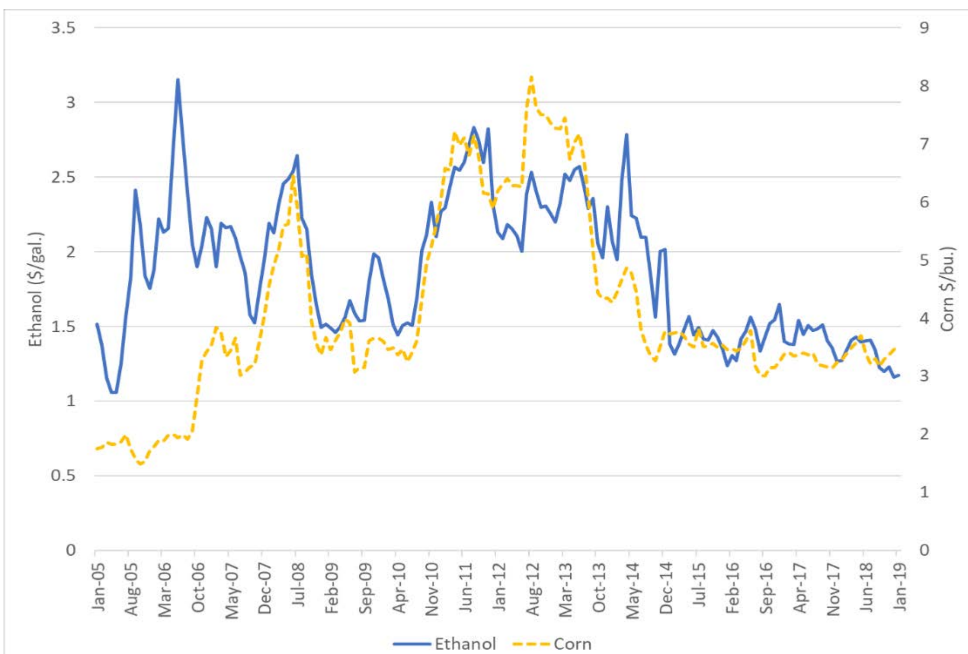

Figure S8 | Ethanol and Corn Prices

Source:Iowa State Agricultural Marketing Resource Center (2019)

In a 2008 study, Abbott et al. (2008) did a comprehensive analysis of the key drivers of commodity and food price increases in 2006-08. 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 (Trostle, 2008). 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 (Shrestha, 2019).

1.3 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 (Abbott, 2009). 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.

1.4 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 (Abbott, 2011). 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(Abbott, 2014; Tyner and Viteri, 2010), but ethanol exports increased substantially over that period as shown in Figure S9. 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 S7) 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 (Irwin, 2019).

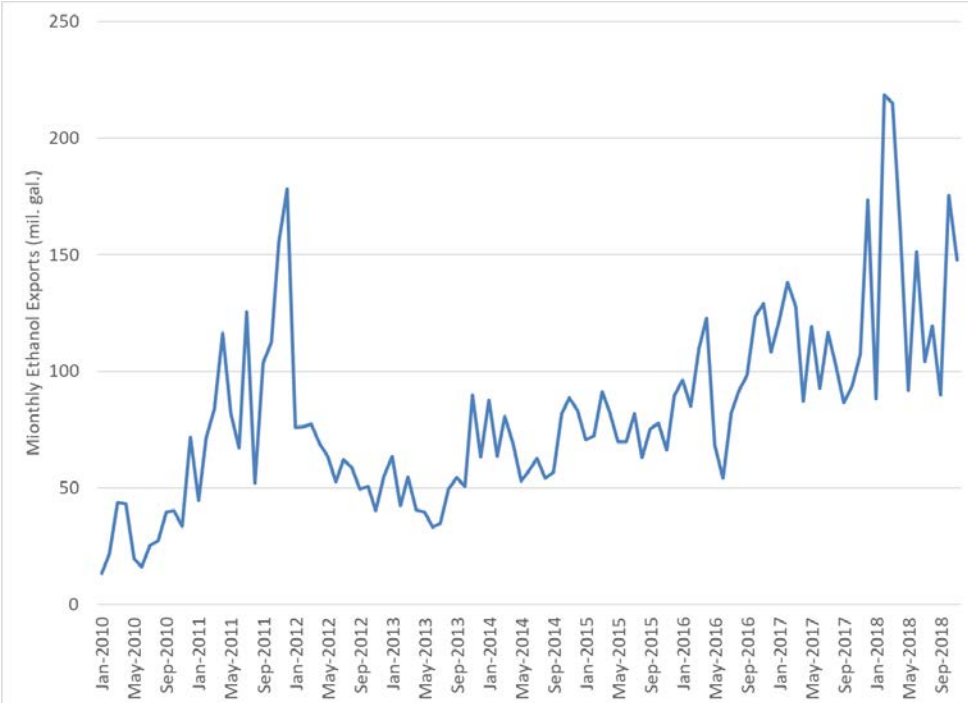

Figure S9 | Monthly Ethanol Exports (2010-2018)

Source: (Renewable Fuels Association, 2019)

1.5 2011-2016 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 S8) which led to negative ethanol margins according to the Iowa State Ethanol Profitability model and as illustrated in Figure S10 (Agricultural Marketing Resource Center, 2019). As a consequence, ethanol production declined (Figure S1) as capacity utilization fell. Also, ethanol exports declined over this same period (Figure S9).

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] Tyner and Viteri, 2010; Tyner et al., 2010). 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.

[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.

First, the great recession of 2008-09 led to a large drop in gasoline consumption, and consumption 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 S2 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 S2 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 S2 | 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.

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

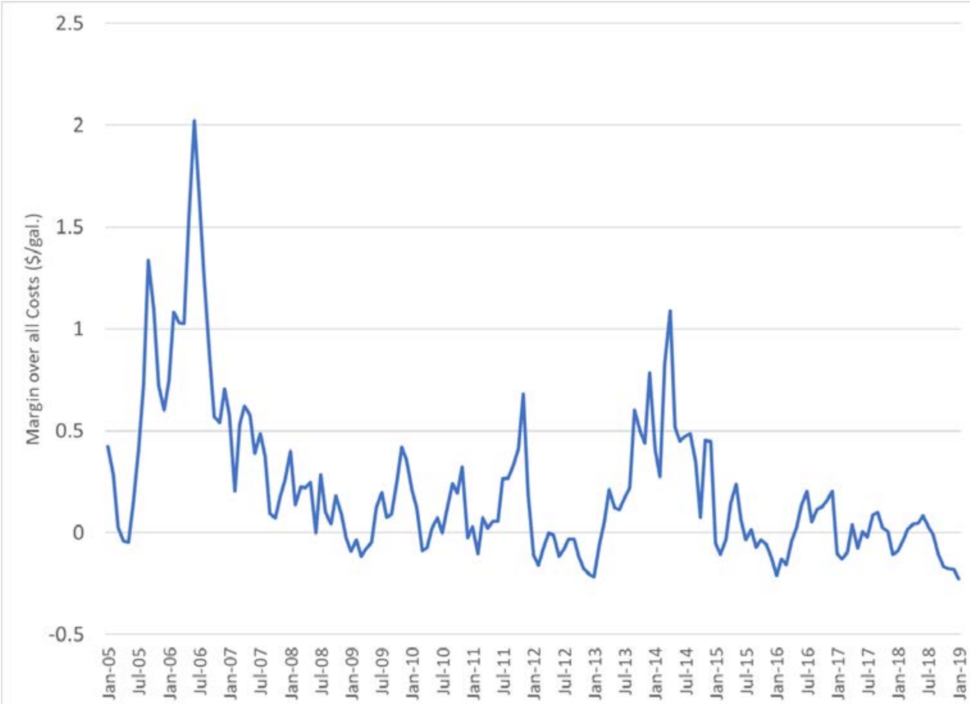

Figure 10 | Ethanol Profitability Margins

Source: (Agricultural Marketing Resource Center 2019)

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 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 S11. 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 S11. 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 (Korting et al., 2019).

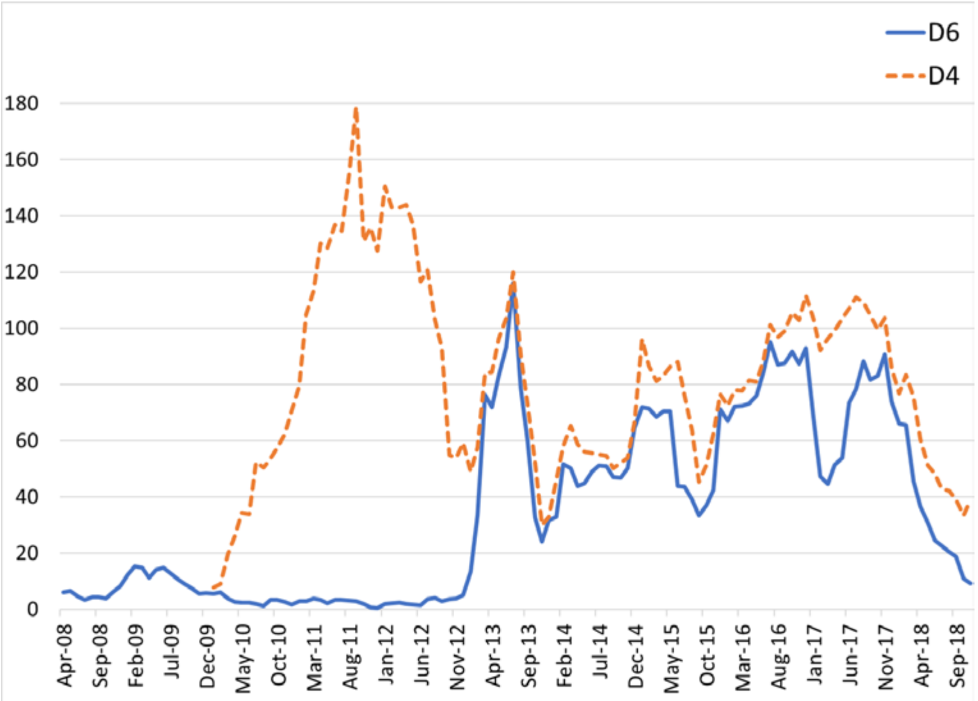

Figure 11 | Monthly Average D6 (ethanol) and D4 (Biodiesel) RIN Prices

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 (Taheripour et al., 2014), which led to a 57% increase in US crude oil production between 2011 and 2016 (Figure S12). This remarkable increase in US production helped push world crude oil prices lower as shown in Figure S2. In addition, energy prices in general have fallen about 37% since 2011 (U.S. Energy Information Administration, 2019c). 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 (U.S. Energy Information Administration, 2018).

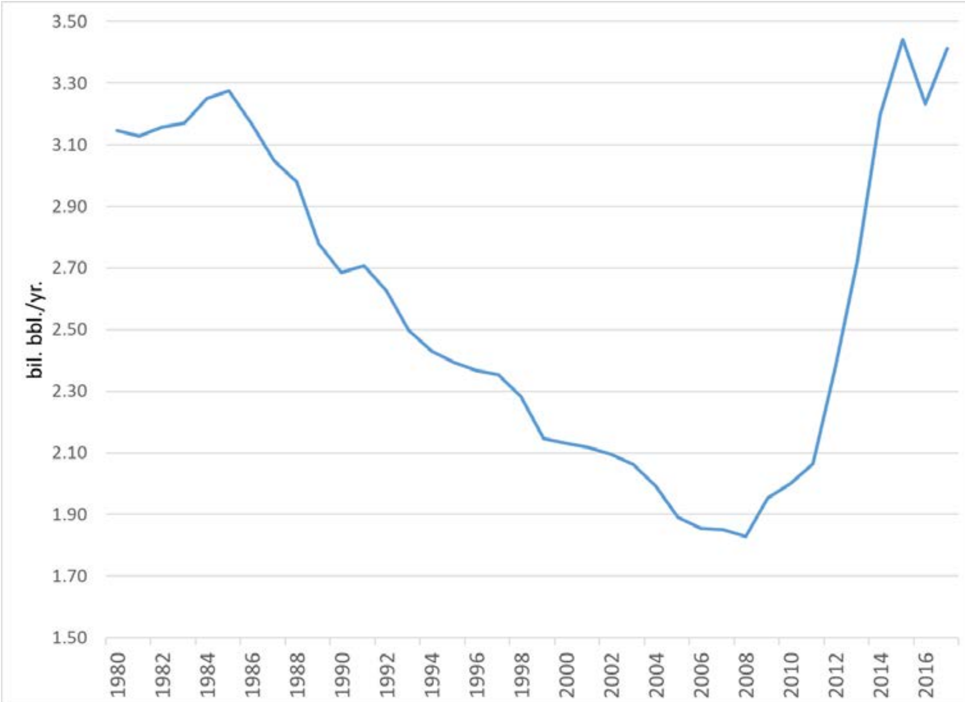

Figure 12 | US Annual Crude Oil Production (1980-2017)

Source: (U.S. Energy Information Administration, 2019d)

1.6 Time Varying Relationships Among Commodity Prices

In addition to the studies mentioned above, USDA has published some important papers on the food-fuel issue (Trostle, 2008; Trostle, 2011). The USDA Chief Economist, Joseph Glauber provided important Congressional testimony indicating that agricultural commodity costs on average represent only 14% of the food dollar (U.S. Department of Agriculture, 2013). There have been many econometric studies of the relationships among prices of crude oil, gasoline, ethanol, corn, and other commodities (Chiou-Wei et al., 2019; Filip et al., 2019; Wright, 2011; Zhang et al., 2010).

Filip et al. (2019) 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 Zhang et al. concluded that there was only a weak relationship between ethanol and agricultural commodities between 1989 and July 2008 (see Figure S3). 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 (Mitchell, 2008; Wright, 2014). 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. (2019) 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 (2014) 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 (Tyner, 2010). For what he called the food crisis and great recession periods, Abbott (2014) calculated correlation coefficients of 0.94 and 0.96, respectively. For similar periods Tyner (2010) 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 (Glauber, 2013; Filip et al., 2017). 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.

1.7 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 (Carter et al., 2017), while the second used a similar approach but added soybean and wheat markets (Smith, 2019). 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.

1.8 Conclusions for literature review and data analyses

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.

2 Additional Supplementary Tables

Table S3 | 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 S4 | 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 FAOSTAT

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