The Effect of the US Ethanol Mandate on Corn Prices

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Abstract

World food prices doubled between 2000 and 2011, and they have increased further in 2012 due to a severe drought in the midwestern United States. How much of this recent jump in food prices can be attributed to the increased use of food crops to produce biofuel? US legislation passed in 2007 requires that a large quantity of corn be converted into ethanol for fuel use. In fact, corn-based ethanol production in the United States has quadrupled since 2005 and now uses 15 percent of all corn produced in the world. In this paper, we estimate what the price of corn would have been if no growth in corn-based ethanol production had been mandated. Using modern time-series methods, we estimate that corn prices were about 30 percent greater between 2006 and 2011 than they would have been without the mandate. We isolate the channels that generate this price increase, including an increase in corn storage in anticipation of ethanol-production increases. We also estimate the extent to which ethanol production exacerbated the effects of the 2012 drought. We find that corn prices would have been about 40 percent lower in 2012 were it not for the mandate. As a result, the impact of US energy policy on global corn prices is considerable, particularly for the world's poor.

"There is fuel in corn; oil and fuel alcohol are obtainable from corn, and it is high time that someone was opening up this new use so that the stored-up corn crops can be moved."
—Henry Ford (in collaboration with Samuel Crowther), *My Life and Work* (1922, p. 276)

1. Introduction: Brief History of Ethanol Production in the United States

More land is now planted with corn than with any other crop in the United States. In 2011, 40 percent of US corn was used to make ethanol slated to be blended with gasoline, up from 14 percent in 2005. The federal government mandated this rapid growth through the Renewable Fuel Standard (RFS), which requires a minimum annual quantity of ethanol content in gasoline. The RFS was introduced in the US Energy Policy Act of 2005. In 2007, under the provisions of the US Energy Independence and Security Act, mandated ethanol use almost doubled. Under the expanded RFS, corn ethanol now comprises 10 percent of finished motor gasoline in the United States, up from 3 percent in 2005. We estimate using a structural vector autoregression that the 2007 expansion in the RFS caused a persistent 30 percent increase in global prices of corn.

Ethanol production causes diverts a substantial amount of grain out of the food system. In 2011, the net loss to the food system from US corn-ethanol production was about 3.3 percent of global grain production.[1] This volume of grain is substantial: it exceeds total corn consumption in all of Africa and in all countries other than China. (It also exceeds

[1] About 15 percent of the world's corn was used to make ethanol in 2011. Since corn comprises one-third of world grain production, about 5 percent of the world's grain production was used to produce ethanol in 2011. After the ethanol is produced, about one-third of the caloric value of the corn is retained in a by-product called distiller's grains, which can be fed to animals, so the net loss to the food system equals two thirds of 5 percent, i.e., 3.3 percent. For more detail on grain production and use, see the USDA World Supply and Demand Estimates, available at http://www.usda.gov/oce/commodity/wasde/.

total rice consumption in all countries other than China and India.) The price effects of turning food into fuel, which we quantify in this paper, are particularly devastating for consumers in less-developed countries, where a relatively large percentage of income is spent on food, and where grains, rather than processed foods, constitute the major portion of the diet.[2] Ivanic, Martin, and Zaman (2011) estimate that when the World Bank's food-price index jumped by approximately 30 percent in 2010, 44 million people were forced below the extreme poverty line of US $1.25 per day.

Although ethanol became a significant motor-fuel ingredient in the United States only recently, its history as a prospective motor fuel is long. In 1920, the US Geological Survey estimated that peak petroleum production would be reached within a few years (White 1920). This assessment raised expectations that ethyl alcohol (i.e., ethanol), distilled from grains and potatoes, would become the dominant motor fuel.[3] At about this same time, European agricultural production recovered from World War I, which caused US agricultural prices to drop. These lower prices motivated US agricultural producers to look to ethanol as an alternative market for their crops. This effort intensified in the 1930s, when the Great Depression brought further hardship to rural America.[4] However, ethanol

[2] According to the Food and Agriculture Organization (FAO) of the United Nations, grains comprised 57 percent of calories consumed in least-developed countries in 2007 but only 22 percent in the United States and 27 percent in the European Union. See http://faostat.fao.org/site/609/default.aspx and the *FAO Statistical Yearbook*.

[3] Newspaper articles expressing this expectation include "Big Future for Alcohol," *Los Angeles Times*, 11/2/1919; "What's Coming in Fuel Drama?" *Los Angeles Times*, 9/12/1920; "Auto Fuel Problem," *New York Times,* 4/27/1919; Alcohol as a Fuel," *New York Times,* 10/19/1919; "More Alcohol Wanted," *New York Times,* 2/13/1921; and "Ford Predicts Fuel from Vegetation," *New York Times,* 9/20/1925, among many others. Carolan (2009) studies peer-reviewed and popular press reports from this period and finds that alcohol fuel had strong support among scientists, automobile engineers, and farmers.

[4] The Farm Chemurgic Movement was the most prominent agricultural advocate. D. Wright (1993) writes that in the early days of the New Deal, members of this movement worked closely with the US Department of Agriculture (USDA) on a farm-relief program that would subsidize ethanol production from farm crops.

production did not become profitable because newly discovered oil reserves in the US Southwest kept petroleum production high and prices low. These low prices, coupled with the fact that ethanol is 35 percent less efficient than gasoline when used to power standard combustion engines, kept ethanol from being profitable as a motor fuel. Thus, ethanol did not become a major motor-fuel ingredient without significant government support, a fact that is readily admitted by the industry.[5]

Although the Renewable Fuel Standard was not enacted until 2005, bills containing variants of the RFS repeatedly entered the US Congress (in 1978, 1987, 1992, 2000, 2001, 2003, and 2004), where they consistently garnered strong support from the corn lobby.[6] The first of these bills, the 1978 Gasohol Motor Fuel Act, proposed that production of alcohol motor fuel supply at least 1 percent of US gasoline consumption by 1981, 5 percent by 1985, and 10 percent by 1990. Although this bill never became law, a weaker version of the proposal was included in the Energy Security Act of 1980. Rather than mandating ethanol production, the 1980 legislation directed the Departments of Energy and Agriculture to prepare and evaluate within the next year a plan "designed to achieve a level of alcohol production within the United States equal to at least 10 percent of the level of gasoline consumption within the United States." However, the ensuing report concluded that this ethanol-use target, "though technologically attainable, is not economically feasible

[5] "The frustrating fact is, without the carrot and stick of government policy, we would not have seen the growth in ethanol that we have seen." Bob Dinneen, President and CEO, Renewable Fuels Association, State of the Industry Address, 17th National Ethanol Conference, 2/23/12.

[6] The Gasohol Motor Fuel Act of 1978 (S.2533), the Ethanol Motor Fuel Act of 1987 (H.R.2052, S.1304), Amendment to the Energy Policy Act of 1992 (H.AMDT.554), Renewable Fuels Acts of 2000 and 2001 (S.2503 and S.670.IS), and the Energy Policy Acts of 2003 and 2004 (H.R.4503, S.2095).

even under optimistic market scenarios" (USDA and USDOE, 1983). As a result, ethanol constituted less than one percent of finished motor gasoline in 1990.

The 1990 amendments to the Clean Air Act provided the next opportunity for the corn-ethanol industry to lobby for favorable legislation. The amendments required that, in regions prone to poor air quality, oxygenate additives be blended into gasoline to make it burn more cleanly. When the amendments were first introduced to Congress in 1987, ethanol and methyl tertiary butyl ether (MTBE), a natural-gas derivative, were the main contenders to fulfill the oxygenate requirement. Johnson and Libecap (2001) document the lobbying battle between advocates for ethanol and those for MTBE. Although ethanol received some favorable treatment in the final legislation,[7] MTBE became the dominant additive because it was less expensive (Rausser et al. 2004). Subsequently, however, leaks in underground storage tanks caused MTBE to contaminate drinking water in numerous cities, and MTBE was consequently banned in at least 25 states.

The demise of MTBE allowed ethanol to establish itself as a fuel additive in the 2005 Energy Policy Act, which essentially replaced the earlier oxygenate requirement with the Renewable Fuel Standard. The RFS mandates that a minimum quantity of ethanol be blended into gasoline in the United States each year. The 2005 RFS mandated that 4 billion gallons (b gal) of ethanol be used in 2006 and that the amount rise gradually to 7.5b gal by 2012. This 2012 quantity corresponded to 5 percent of projected domestic gasoline use, so it represented a small expansion of the proportion of oxygenates in gasoline. In 2005, US

[7] Ethanol was allowed a 1 lb. waiver in the Reid Vapor Pressure (RVP) requirement.

oxygenate production (ethanol and MTBE combined) totaled 4.6 percent of finished motor gasoline supplied.

Legislation to increase the RFS entered Congress even before the 2005 Energy Policy Act had passed, and more bills followed in 2006.[8] These proposals led the RFS for corn ethanol to be doubled in 2007. The 2007 RFS specifies minimum renewable-fuel production each calendar year from 2007 through 2022. It required 9b gal in 2008 and increased this level annually to 15.2b gal in 2012 and 36b gal in 2022. However, the 2007 RFS specified that no more than 13.2b gal of corn ethanol could be used to satisfy the RFS in 2012, and no more than 15b gal of corn ethanol could be used after 2015. The balance of the RFS, the legislation stipulated, had to be filled by so-called advanced biofuels, such as biodiesel from soybean oil and ethanol from cellulosic biomass (e.g., switchgrass, miscanthus, and corn stover). But as of 2011, no commercially viable cellulosic ethanol refineries existed in the United States (National Academy of Sciences 2011).

Not surprisingly, a massive expansion in ethanol production capacity took place between the 2005 and the 2007 Energy Acts.[9] At the beginning of 2006, 4.3b gal of operational production capacity existed, and an additional 1.8b gal of capacity was under construction. Only one year later, capacity under construction had grown to 5.6b gal, which exceeded the previous year's total ethanol production (see Panel A of Figure 1). This construction boom, which anticipated the expansion of the RFS, received considerable attention. The United States Department of Agriculture (USDA), which makes annual 10-

[8] 20/20 Biofuels Challenge Act of 2005 (S.1609), BOLD Energy Act of 2006 (S.2571.IS, H.R.5331.IH).

[9] In the remainder of this article, we use the word *ethanol* to refer to ethanol made from corn. Only trivial amounts of other feedstock have been used commercially in the United States to produce ethanol for motor fuel.

year projections of the agricultural economy, recognized the expanding RFS and the associated construction boom in its 2007 projections.[10] Panel B of Figure 1 shows that the projections the USDA made in February 2007 (the solid black line) almost doubled the 2006 projections (the solid gray line). These 2007 projections predicted 2007–09 ethanol use extremely well. In contrast, the February 2006 projections understated 2008 and 2009 ethanol use by 33 and 39 percent, respectively. Panel B of Figure 1 also shows that the 2007 expanded RFS almost doubled the ethanol mandate. Overall, Figure 1 reveals that the 2007 expansion of the RFS generated a large jump in projected ethanol production.

[FIGURE 1 HERE]

In addition to the RFS, numerous other federal and state policy actions have aimed to expand ethanol production. Koplow (2007) estimates that total government support for biofuels (mostly ethanol) reached $7 billion in 2006; he projected that this support level would reach $13 billion in 2008. The 1978 Energy Tax Act marked the beginning of federal ethanol programs; it included a provision to exempt ethanol-gasoline blends from the gasoline excise tax. Subsequent legislation added further support for domestic ethanol by offering loan guarantees for ethanol-plant investment and instituting a tariff on imported ethanol.[11] The excise-tax exemption evolved into a tax credit, which, in 2011, was worth about $6 billion. The ethanol tax credit and the import tariff both expired on December 31, 2011 with little opposition from ethanol producers' groups such as the National Corn Growers Association and the Renewable Fuels Association.[12] This quiet surrender reveals

[10] Available at http://usda01.library.cornell.edu/usda/ers/94005/.
[11] Omnibus Reconciliation Act of 1980 and Energy Security Act of 1980.
[12] "With growing concerns about gridlock in Washington and greed on Wall Street, Americans are wondering whether anyone with a stake in public policies is willing to sacrifice their short-term advantage for a greater

the high value of the RFS to the ethanol industry; with the RFS in place, it has acquired guaranteed demand for its product and a large implicit subsidy (Holland et al. 2011).

Another significant issue related to corn-ethanol production is the unresolved question of whether corn-ethanol really reduces greenhouse-gas emissions. Ethanol production from corn requires a substantial amount of fossil energy: about 0.8 Btu of fossil fuel is needed in order to produce 1 Btu of energy from corn ethanol (Searchinger et al. 2008). Second, to the extent that ethanol subsidies lower the price of gasoline, they may increase the quantity of gasoline demanded and thereby lessen the reduction in fossil-fuel use they were supposed to achieve (de Gorter and Just 2010; Khanna, Ando, and Taheripour 2008). Finally, after accounting for the fact that higher corn prices give farmers around the world incentives to cultivate more land, the overall impact of ethanol on greenhouse gas emissions is at best unclear, and at worst negative (Searchinger et al. 2008; Tyner 2008).

2. Quantifying the Effect of Increased Ethanol Production on Corn Prices

Previous studies have argued that corn-ethanol production affects corn prices. The International Food Policy Research Institute (IFPRI, 2008) and the OECD (2008) have both asserted in well-publicized reports that biofuels were responsible for a significant proportion of the corn-price increase during the 2007–08 commodity boom (see also Helbling et al. 2008). Other studies assert that ethanol policy strongly affected the level (Mitchell 2008; Runge and Senauer 2007; Hochman, Rajagopal, and Zilberman 2010) and

good. Well, someone just did. Without any opposition from the biofuels sector, the tax credit for ethanol blenders (the Volumetric Ethanol Excise Tax Credit—VEETC) expired on January 1." Bob Dinneen, President and CEO, Renewable Fuels Association, 1/5/12. RFA press release.

the volatility (Wright 2011) of corn prices. But each of these papers is mainly qualitative; none provides rigorous empirical estimates to support its conclusions. In contrast, Roberts and Schlenker (2010) estimate the elasticities of world supply and demand for calories from storable commodities. They create a calorie-weighted index of prices and quantities and use instrumental-variables techniques to estimate the parameters. Based on a static model, they estimate that their food price index was 20 percent higher in 2007 than it would have been without any ethanol production.

We focus on inventory dynamics in our analysis for two reasons. First, Figure 1 shows that informed market participants would have been well aware by late 2006 of the impending boom in ethanol production. Therefore, we would expect to see that a shift in inventory demand occurred around this time. Failure to account for this inventory-demand shift could cause us to underestimate the ethanol-induced corn price increase because that price increase occurred *before* the jump in ethanol production. Second, any price response to a supply or demand shock depends on the level of inventory. Plentiful inventory serves as a buffer in the face of negative supply or positive demand shocks and so mitigates the effect of these shocks on prices. When inventory is low and there is no inventory-supply buffer, even a small shock can cause a large price spike (Wright 2011). Thus, in order to model the price response to the ethanol-induced demand shock, we must account for inventory dynamics.

We estimate the supply and demand for inventory using a partially identified structural vector autoregression. This approach enables us to traces the dynamic effects of ethanol expansion without imposing strong identifying assumptions. We find that corn prices were 39 percent greater in log terms[13] in 2011 than they would have been if US ethanol production had stayed constant at the 2005 level. We also estimate that average prices over the period from 2006 to 2011 were 30 percent greater than they would have been if the increase in ethanol production had not occurred. This average for the seven-year period is lower than the 2011 effect because the market was able to buffer the initial stages of the ethanol boom by increasing inventories in anticipation of the coming growth in ethanol production. We estimate that the demand for corn inventory increased during the 2006–07 crop-year, as firms sought to store corn for the ethanol-production boom that would follow in 2008 and beyond. This increase in inventory demand helped to buffer the market in 2009–10, when ethanol production increased dramatically. But by 2012, inventories had been depleted, leaving the markets vulnerable to production shortfalls and price spikes.

3. Conceptual Framework

In this section, we present a conceptual model to motivate our empirical strategy. Our core framework consists of a two-period model of a grain commodity that incorporates three markets: (i) supply and demand for use in the first period; (ii) supply and demand for use in the second period; and (iii) storage from period 1 to period 2. We represent supply and demand for use in the two periods as

$$\begin{aligned} D_1 &= \alpha_0 - \alpha_1 P_1 + \eta_1^D \\ D_2 &= \alpha_0 - \alpha_1 P_2 + \eta_2^D \\ S_1 &= \eta_1^S \\ S_2 &= \beta_0 + \beta_1 E_1[P_2] + \eta_2^S, \end{aligned} \tag{1}$$

[13] When reporting our results, we use the word *percent* to refer to log differences.

where D_t and S_t denote quantity demanded and supplied, and η_t^D and η_t^S denote demand and supply shifters. The demand function accumulates all sources of current-period demand for feed, seed, food, ethanol, and export use. There are no imports.[14] Supply in period 2 is determined by the expected price at the end of period 1. Period 1 supply is fixed; it includes the period 1 harvest and any carryover inventory coming into period 1.

Given (1), the net supply for use in each period is

$$S_1 - D_1 = -\alpha_0 + \alpha_1 P_1 + \eta_1^S - \eta_1^D \tag{2}$$

$$S_2 - D_2 = \beta_0 - \alpha_0 + \beta_1 E_1[P_2] + \alpha_1 P_2 + \eta_2^S - \eta_2^D. \tag{3}$$

Period 1 net supply represents the market's willingness to supply inventories. At any price above the level that would leave net supply equal to zero in period 1, there exists a positive supply of inventory. Inventory demand comes from expectations about the following period's net demand. At any price below the level that would leave expected period 2 net demand equal to zero, there exists a positive demand for inventory. A principal cause of period 2 supply shocks is realized weather, which is difficult or impossible to forecast. Moreover, a major source of demand shock comes from the export market, which is affected by weather shocks in other producing countries. Thus, at the beginning of period 2, $\eta_2^S - \eta_2^D$ in (3) is largely unpredictable.

The storage market connects the two periods. Storage firms purchase the excess supply in period 1, hold it for one period, and sell it into the period 2 market. The price of storage equals the difference between the expected period 2 selling price and the period 1 price; that is, the price of storage is $E_1[P_2] - P_1$. Following a long literature that originates

[14] US corn imports are essentially zero.

with Working (1949), we specify the marginal cost of storage as increasing with inventory. This specification leads to the well-known "Working curve" for the supply of storage. For illustration, we use the specification

$$SS_1 = \gamma_0 + \gamma_1 \ln(S_1 - D_1) + \eta_1^{SS} \qquad \text{supply of storage.} \qquad (4)$$

This specification imposes the constraint that inventory carryover cannot be negative, which implies $S_1 \geq D_1$. The marginal cost of storage can, however, be negative. A negative marginal cost of storage can arise due to convenience yield, a concept introduced by Kaldor (1939) and developed by Brennan (1958), among others. Convenience yield represents the flow of benefits to firms that hold the commodity in storage. It is typically motivated as an option value generated by transactions costs associated with sourcing the commodity (Telser 1958) or by the possibility that inventories could be driven to their lower bound (Routledge, Seppi, and Spatt 2000).

We use the terms *inventory* and *storage* in the same way they are used in the commodity-storage literature. However, these terms leave room for confusion. *Inventory* denotes actual bushels of grain that are not used in period 1 and are instead saved for use in period 2. *Storage* describes the service of holding the commodity from period 1 to period 2. To use an analogy in the retail industry, inventory corresponds to the units of product that a store buys from wholesalers and sells to consumers, and storage corresponds to the service of buying the product from wholesalers and selling it to consumers. The price of storage thus corresponds to the markup earned by retailers, whereas the price of inventory is the price of a unit of the commodity.

The retail analogy helps clarify the demand for storage services in our model. The willingness to pay for retail services equals the difference between the price at which consumers are prepared to buy a unit in the store and the price at which wholesalers are willing to sell that unit to the store. Similarly, the demand for storage is the vertical difference between the inventory supply and demand curves. Inverting the supply and demand for inventory in (2) and (3), we have

$$P_1 = (\alpha_0 + I_1 - \eta_1^S + \eta_1^D)/\alpha_1 \qquad \text{inverse inventory supply} \tag{2a}$$

$$E_1[P_2] = (\alpha_0 - \beta_0 - I_1 - E_1[\eta_2^S - \eta_2^D])/(\beta_1 + \alpha_1) \qquad \text{inverse inventory demand.} \tag{3a}$$

Thus, the willingness to pay for storage is the difference between (3a) and (2a), that is, the inverse demand for storage is

$$DS_1 = (\alpha_0 - \beta_0 - I_1 - E_1[\eta_2^S - \eta_2^D])/(\beta_1 + \alpha_1) - (\alpha_0 + I_1 - \eta_1^S + \eta_1^D)/\alpha_1. \tag{5}$$

The demand for storage slopes downward because the market desires to save more inventories for the second period when the price of storage is low.

Figure 2 illustrates the equilibrium. Panel A reflects the period 1 supply and demand curves. The horizontal difference between these curves is inventory supply, denoted by S_1–D_1 in Panel C. Panel B shows the expected period 2 supply and demand curves. The horizontal difference between them is shown in Panel C as inventory demand, denoted $E_1[D_2 - S_2]$.

[FIGURE 2 HERE]

The inventory demand and supply curves in Panel C are each evaluated at different prices. The inventory supply curve is evaluated at the period 1 spot price P_1, and the inventory demand curve is evaluated at the expected period 2 spot price $E_1[P_2]$. Thus, the vertical difference between these curves equals the price-dependent demand for storage in (5). The market will clear at the point where the inventory supply and demand curves cross only if the market price of storage is zero. Panel D depicts the demand for storage derived from Panel C and plots that demand along with the supply of storage. In this example, the market clears at an inventory level with a positive price of storage, (i.e., $E_1[P_2]-P_1>0$). If the demand for storage were to shift left, then this equilibrium could occur with a negative price of storage (i.e., futures-market inversion or backwardation).

In the case of ethanol, evidence shown in Figure 1 suggests that by the end of 2006, market participants knew that ethanol production would increase in 2008. Viewed in light of Figure 2, the demand-for-inventory curve shifted to the right in 2006, but the supply-of-inventory curve did not shift fully until 2008. The results of this delay in inventory supply were increases in spot prices, inventory levels, and prices of storage. By 2008, the increase in demand from ethanol plants had become permanent. In the context of Figure 2, the supply-of-inventory curve in panel D had shifted to the left, while the inventory-demand curve had shifted to the right.

Figure 3 represents the effect of an increase in demand in both periods. From the perspective of the inventory market, both current-supply and current-demand shocks affect the amount of available inventory. It matters little whether the reduced supply of inventory comes from bad weather (which reduces the crop size) or from increased demand (which removes more of the commodity from the market). This feature of our framework helps us identify the effects of ethanol, because we do not need to estimate separate elasticities of demand and supply for current use.

[FIGURE 3 HERE]

Figure 3 shows a decline in inventory carryover because the perfectly inelastic supply in period 1 causes the supply-of-inventory curve to shift up by more than the demand-for-inventory curve. The graphical analysis illustrates the case in which the market is surprised, in period 1, by the demand shift. The market responds by drawing down inventory. If, in period 0, the market had anticipated the coming demand shift, it would have increased period 1 supply. Relative to the case depicted in Figure 3, the supply-of-inventory curve would have shifted to the right, and the inventory carryover would have increased.

Admittedly, our presentation of inventory supply and demand is somewhat unconventional. A more conventional approach (e.g., Carter and Reveredo-Giha 2009; Wright 2011) is to focus on period 1 and to express total demand for the commodity as demand for period 1 use (D_1 in Figure 2) plus the demand for inventory. In this more conventional framework, the demand for inventory includes the price of storage. As inventory carryover approaches zero, total demand becomes less elastic. (Wright [2011] highlights this feature of storable-commodity prices: when inventory is low, the lack of a buffer means that even small shocks can have large price effects.) We separate the demand for inventory from the demand for current use for two reasons. First, this approach enriches the theory by making predictions not just about the effects of ethanol on corn prices, but also about the effects on the price of storage. Second, the kink in the total demand curve at low inventory levels means that linear models of total demand are not correctly specified. By modeling inventory supply and demand directly, we avoid this misspecification.

4. Empirical Framework

In Section 3, using a two-period model, we show how demand from ethanol producers for corn affects the supply and demand for inventory, the price of storage, and the price of corn. In reality, of course, such effects continue after the second period; shocks may persist for multiple periods, and inventory need not be exhausted in the second period. To represent this reality, we estimate a structural vector auto-regression (SVAR) model that includes supply-of-inventory, demand-for-inventory, and supply-of-storage equations. Using this framework, we follow a long literature pioneered by Sims (1980) concerning estimating dynamic rational-expectations models with SVARs. Our identification scheme (which we describe in Section 4.2) allows us to partially identify shocks to each of inventory demand, inventory supply, and the supply of storage, and the estimated parameters then reveal how these shocks propagate through the system.

We use annual data covering the period 1961 through 2011. We choose to model at the annual frequency because price and inventory variation is dominated by the annual harvest cycle.[15] We use futures prices for the next period's expected price. In addition to prices and inventory, we follow Kilian (2009) in controlling for aggregate commodity demand. After we describe our data, we present our identification strategy in Section 4.2 and specify our counterfactual experiment in Section 4.3.

[15] Inventory data exist for the United States at the quarterly frequency. These data exhibit a saw-tooth pattern: the fall harvest generates high inventory in December, and inventory declines linearly in each of the three subsequent quarters. Because futures contracts are traded continuously, futures-price data exist at a very high frequency.

4.1 Data

In this section, we describe how we construct each of the four core variables in our model.

4.1.1. Real Futures Price of Corn

The crop-year for corn in the United States runs from September through August. The crop is typically planted in April and May and harvested in September and October. Through the summer, the growing regions experience agro-economic conditions (especially precipitation and temperature) that determine productivity (yields). If the weather is too hot, cold, wet, or dry, then prices rise in anticipation of a small crop. After harvest, it takes some time before the size of the harvest is known. The official scorekeeper, the USDA, publishes its final estimate of the crop size in January, following the harvest. However, after November, the USDA usually revises its estimates only slightly.

We measure prices in March of each year, which occurs in the middle of the crop-year, before the weather realizations occur that determine yield on the next year's output, and after the market has full information about the size of the previous year's output. Specifically, for each year we take the average price across all days in March on the futures price for delivery in December. This price represents the (risk-adjusted) price that a firm would expect to receive in December if it were to decide in March to sell corn in December. We then deflate the price by the all-items consumer price index and take logs. The resulting futures-price variable is $f_t = \ln\left(F_{t,T} / CPI_t\right)$, where t denotes March of each year and T denotes December of the same calendar year.

4.1.2. Futures Cash Price Spread (Convenience Yield)

As articulated by Working (1949), the market price of storage is revealed by the difference between the futures price for delivery after the next harvest and the current spot price. In other words, the absence of arbitrage opportunities implies that the futures price equals the current cash price plus the cost of carrying the commodity until the futures contract expires. Specifically,

$$F_{t,T} = \left(P_t(1+r_{t,T}) + c_{t,T}\right)(1-y_{t,T}), \qquad (6)$$

where $r_{t,T}$ denotes the cost of capital, $c_{t,T}$ the warehousing cost of storage, and $y_{t,T}$ the convenience yield. With this construction, we can interpret the convenience yield as the percent by which the futures price falls below the value implied by full carrying costs.

Each day, the Agricultural Marketing Service of the USDA collects cash grain-bid prices from grain elevators throughout the Corn Belt. It reports average bid prices daily according to location. Central Illinois is a common benchmark location for corn because a large quantity of corn flows through this region. Accordingly, we use Central Illinois cash bids to measure the current spot price (although it does not make any difference to our results if we use other locations in the United States). Garcia, Irwin, and Smith (2012) show that the specific futures-market delivery institution sometimes causes the futures price to exceed the expected future spot price. However, they show that although these discrepancies have recently been large for wheat, over a nine-month storage window, they are small for corn. Moreover, our results do not change if we use expiring March futures prices in place of Central Illinois cash bids.

We treat capital costs as exogenous to corn storage. We measure the cost of capital using the yield on one-year Treasury notes plus 200 basis points. (We add 200 basis points based on the Chicago Mercantile Exchange's method for determining the price of storage in wheat-futures markets.) The one-year Treasury is consistent with a nine-month storage period. Thus, our measure of capital costs associated with grain storage is

$$r_{t,T} = 0.75 g_t \, , \tag{7}$$

where g_t denotes the annual capital cost of storage and the 0.75 factor reflects the fact that we are calculating the cost of storage over a nine-month horizon. Our results are insensitive to the choice of capital-cost measure because variation in the price of storage is dominated by variation in the other components of (6).

Warehousing fees are not directly observable from secondary sources. Moreover, because grain elevators are multi-output firms that merchandize and store several different commodities and may cross-subsidize some activities, a posted fee for storage may not clearly reflect the price of grain storage on the margin (Paul 1970). Our warehousing-cost factor is derived from a maximum storage price set by the Chicago Mercantile Exchange on warehouse receipts and shipping certificates that are issued to make delivery on futures contracts. Since 1982, this price maximum has been between \$0.045 and \$0.05 per bushel per month. However, Garcia, Irwin, and Smith (2012) show that this price has been too low relative to the market in the last several years, and that \$0.10 would be a more appropriate price. The lower price appears to have been quite appropriate when it was first implemented (in 1982–83). If the storage price had been allowed to grow at the rate of CPI inflation, it would have reached \$0.10 in 2007. Thus, we define the warehousing component of the price of storage as \$0.05/bu/mo in 1982–83 dollars, which corresponds to \$0.45 over the nine months from March to December.

Taking logs, the spread variable we use in our estimation is:

$$cy_t = -\ln(1-y_{t,T}) = \ln\left(\frac{P_t(1+0.75g_t)}{CPI_t}+0.45\right) - \ln\left(\frac{F_{t,T}}{CPI_t}\right), \tag{8}$$

where CPI is indexed to equal 1 in 1982–83.[16]

4.1.3. Crop-Year-Ending Inventory

We use crop-year-ending inventory in the United States as the quantity variable in our model. This variable measures total corn inventory on August 31 of each year—that is, five months after the month in which we measure price. This timing convention suggests that inventory might be endogenous to price. Specifically, if a demand shock raises the price of the December futures contract in March, firms may respond by increasing inventory demand. We implement a partial-identification strategy to account for this possibility.

We use US inventory rather than world inventory for two reasons. First, US inventory is measured much more accurately than world inventory. Second, although the corn market is global, transportation costs are significant, so prices at any location reflect local scarcity. That is, using US inventory volume totals is commensurate with using a US price. Finally, we include both government- and privately-held inventory. The US

[16] Our estimates of the effect of ethanol expansion on futures prices are robust to our choice to set the warehousing storage cost to \$0.45; the estimated average price effect changes by less than one percentage point if we set the warehousing storage cost to 0. However, setting this price to zero causes the estimated convenience-yield effects from an inventory-demand shock to be of the wrong sign, so we think it is important to include an additive component to the price of storage.

government held large amounts of corn inventory during some parts of our sample period, but the results are very similar if we exclude government stocks. Our inventory variable is $i_t = \ln(I_t)$.

4.1.4. Index of Real Economic Activity (REA)

Rapid economic growth and intense industrial activity tend to coincide, especially in less-developed nations. This growth spurs demand for commodities and raises commodity prices. In a review article (2011), we show that both the 1973–74 and 2007–08 commodity booms were preceded by unusually high world economic growth, especially in middle-income countries. Specifically, as we emphasized in that article, "for the five years leading up to the first boom (1969–73), real GDP grew by 6.6 percent per year in middle-income countries. Similarly, for the five years leading up to the second boom (2003–07), middle-income real GDP grew by 7.2 percent annually. In no year between 1973 and 2003 did middle-income GDP growth exceed 6 percent, and the average over this interim period was 3.8 percent."

Rapid economic growth and industrialization raise energy prices (Kilian 2009), and such increases, in turn, raise the fuel and fertilizer costs of agricultural production. Moreover, as they grow wealthier, consumers in less-developed countries adjust their diets away from simple grain and toward meat. For example, per-capita meat consumption in China increased by a factor of 15 between 1961 and 2009.[17] As a result of this dietary shift, the demand for grain for animal feed increases, so that corn prices increase as well. Additional factors may contribute to the link between global economic activity and corn

[17] Food and Agriculture Organization, available at http://faostat3.fao.org.

prices. Frankel (1986) and Rausser and colleagues (1986) argue that because the prices of grains such as corn tend to be more flexible than retail prices, grain prices may overshoot in response to monetary stimulus. This overshooting phenomenon generates procyclicality in commodity prices.

To represent global economic activity, we use the index developed by Kilian (2009) and extend it backwards using the index of Hummels (2007). These indexes are based on dry-cargo shipping rates and are designed to capture shifts in global demand for industrial commodities. As Kilian emphasizes, “the proposed index is a direct measure of global economic activity which does not require exchange-rate weighting, which automatically aggregates real economic activity in all countries, and which already incorporates shifting country weights, changes in the composition of real output, and changes in the propensity to import industrial commodities for a given unit of real output” (1056).

Figure 4 presents the resulting index of real economic activity (after removing a linear trend) along with the de-trended time-series data for log inventory, log real futures price, and convenience yield.

[FIGURE 4 HERE]

4.2 VAR Model and Identification

Based on the theory outlined in Section 3 and the variables described in Section 4.1, our basic econometric specification is

$$AX_t = BX_{t-1} + \Gamma Z_t + U_t, \qquad (9)$$

where

$$X_t = \begin{bmatrix} REA_t \\ i_t \\ f_t \\ cy_t \end{bmatrix}, \quad U_t = \begin{bmatrix} u_{1t} \\ u_{2t} \\ u_{3t} \\ u_{4t} \end{bmatrix}, \text{and } Z_t' = \begin{bmatrix} 1 & t \end{bmatrix}.$$

The fourth equation represents the supply-of-storage, the third represents inventory demand, and the second represents inventory supply.[18] In the notation of Section 3, these three equations are

$$i_t = \alpha_{23}(f_t + cy_t) \ + \alpha_{21} REA_t + B_2' X_{t-1} + \Gamma_1' Z_t + u_{2t} \qquad \text{inventory supply} \qquad (9a)$$

$$f_t = -\alpha_{32} i_t \qquad + \alpha_{31} REA_t + B_3' X_{t-1} + \Gamma_2' Z_t + u_{3t} \qquad \text{inventory demand} \qquad (9b)$$

$$cy_t = -\alpha_{42} i_t + \alpha_{43} f_t + \alpha_{41} REA_t + B_4' X_{t-1} + \Gamma_3' Z_t + u_{4t} \qquad \text{supply of storage.} \qquad (9c)$$

Because the REA variable is exogenous to corn prices and inventory, we have

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -\alpha_{21} & 1 & -\alpha_{23} & -\alpha_{23} \\ -\alpha_{31} & \alpha_{32} & 1 & 0 \\ -\alpha_{41} & \alpha_{42} & -\alpha_{43} & 1 \end{bmatrix}, B = \begin{bmatrix} \beta_{11} & \beta_{12} & \beta_{13} & \beta_{14} \\ \beta_{21} & \beta_{22} & \beta_{23} & \beta_{24} \\ \beta_{31} & \beta_{32} & \beta_{33} & \beta_{34} \\ \beta_{41} & \beta_{42} & \beta_{43} & \beta_{44} \end{bmatrix} = \begin{bmatrix} B_1' \\ B_2' \\ B_3' \\ B_4' \end{bmatrix}. \qquad (10)$$

The parameter α_{23} is the short-run (i.e., one-year) elasticity of inventory supply. As shown in Figures 2 and 3, this parameter reflects the horizontal difference between the current-year supply and demand curves; it is the difference between the supply- and current-use demand elasticities. The parameter α_{32} is the short-run inverse elasticity of net demand for inventory with respect to the expected price in the next period. Another key parameter is α_{42}, the short-run inverse elasticity of supply of storage, holding the futures price constant. Finally, although the parameter α_{43} is implicitly set to zero in our theory, we have no reason to impose that condition on our empirical analysis. As specified in (9) and (10), these

[18] Our empirical results are robust to additional lags. The AIC and BIC select a single lag.

elasticities are not identified, because inventory is endogenous in the inventory-demand and supply-of-storage equations.

Most of the year-to-year variation in inventory is sourced with fluctuations in inventory supply (i.e., fluctuations in current-year supply and demand). To identify α_{23}, we require independent variation in inventory demand. The dominance of inventory-supply shocks thus makes point identification of α_{23} difficult. As a result, we implement a partial-identification strategy.

Partial identification, also known as set identification, permits econometric analysis without imposing strong assumptions (Manski 2003). We assume that α_{23} lies in a specified range, but we take no position on which value in that range the parameter takes. Because we do not identify a particular value for α_{23}, the other parameters in *A* are also not uniquely identified; they are identified only up to the set defined by our assumption on α_{23}. This approach is similar to that employed by Kilian and Murphy (2011) in their study of the role of inventory in determining crude-oil prices. Kilian and Murphy impose sign restrictions on the elements of their *A* matrix and bounds on several of the short-run elasticities in that matrix. Their method extends the identification-by-sign-restrictions approach of Faust (1998) and Uhlig (2005), who impose sign restrictions only. In our case, we find it credible that there is no feedback from the corn market to global economic activity within one year, so we impose some zero restrictions in *A*. Based on our theoretical framework, we also assume that the convenience yield does not shift the inventory-demand curve. These zero restrictions leave a single unidentified parameter, so we place bounds only on α_{23}. In this sense, our approach is similar to the one Blanchard and Perotti (2002) use to model the effects of government spending and taxes on output. Blanchard and Perotti impose on their model a value for the elasticity of tax receipts with respect to GDP.

To motivate the bounds we place on α_{23}, note that the supply of inventory (I^s) equals quantity supplied (Q^s) minus quantity used (Q^u). Thus, the short-run elasticity of inventory supply with respect to the cash price is

$$\theta^s \equiv \frac{dI^s}{dP}\frac{P}{I} = \frac{dQ^s}{dP}\frac{P}{I} - \frac{dQ^u}{dP}\frac{P}{I} = \left(\eta^s \frac{Q^s}{Q^s} - \eta^u \frac{Q^u}{Q^s}\right)\frac{Q^s}{I}, \tag{11}$$

where we define the production (supply) and current-use demand elasticities, respectively, as $\eta^s \equiv \frac{dQ^s}{dP}\frac{P}{Q}$ and $\eta^u \equiv \frac{dQ^u}{dP}\frac{P}{Q^u}$. Note also that total demand equals demand for current use plus inventory demand (i.e., $Q^d = Q^u + I^d$). Thus, elasticity of total demand is

$$\eta^d \equiv \frac{dQ^d}{dP}\frac{P}{Q^d} = \frac{dQ^u}{dP}\frac{P}{Q^d} + \frac{dI^d}{dP}\frac{P}{Q^d} = \eta^u \frac{Q^u}{Q^d} + \theta^d \frac{I}{Q^d}, \tag{12}$$

where $\theta^d \equiv \frac{dI^d}{dP}\frac{P}{I}$ denotes the elasticity of inventory demand with respect to the spot price P. Using the equilibrium condition $Q = Q^s = Q^d$, these two equations imply

$$\theta^s = \left(\eta^s - \eta^d + \theta^d \frac{I}{Q}\right)\frac{Q}{I}, \tag{13}$$

which can be rewritten as

$$\theta^s - \theta^d = \left(\eta^s - \eta^d\right)\frac{Q}{I}. \tag{13a}$$

That is, the difference between the elasticities of supply and demand for inventory is proportional to the difference between the elasticities of total supply and demand.

Using estimates from the literature and some introspection, we could exactly identify our model by choosing numerical values for the terms on the right-hand-side of (13a). This was the approach used by Blanchard and Perotti (2002). For the total demand elasticity, η^d, we could use the estimates of Adjemian and Smith (2012). They use the price response to USDA crop forecasts during the period from 1980 to 2011 to estimate that the demand flexibility (inverse elasticity) for corn is -1.27, which implies $\eta^d = -1/1.27 = -0.79$. In our setting, the short-run production elasticity, η^s, is close to zero. Since planted acreage and inventory carryover are essentially determined by March of each year, it is nearly impossible for producers to respond to price shocks that occur after March. During our sample period, average year-ending stocks as a proportion of inventory equal 0.18. Thus, at average inventory levels, we expect from (13a) that $\theta^s - \theta^d \approx (0 - -0.79)/0.18 = 4.4$.

To translate θ^s into our econometric specification, we define the spot price of interest as $\log(P) \equiv f + cy$. Then, equations (11)–(13) imply $\theta^s \equiv \alpha_{23}$. Similarly, combining the inventory-demand and supply-of-storage equations (9b and 9c) implies

$$\frac{1}{\theta^d} \equiv \frac{d(f+cy)}{di} = -\alpha_{32}(1+\alpha_{43}) - \alpha_{42}, \tag{14}$$

which implies

$$\theta^d = -1/\left(\alpha_{32}(1+\alpha_{43}) + \alpha_{42}\right). \tag{15}$$

Thus, we translate our expectation that $\theta^s - \theta^d \approx 4.4$ into our econometric model parameters as $\alpha_{23} + 1/\left(\alpha_{32}(1+\alpha_{43}) + \alpha_{42}\right) \approx 4.4$.

To fully identify our model, we could impose the restriction $\alpha_{23}+1/\left(\alpha_{32}(1+\alpha_{43})+\alpha_{42}\right)=4.4$. Instead, we impose only that α_{23} lie in a specified range. Next, we develop this range. A zero short-run production elasticity (η^s=0) implies, from (11), that the elasticity of inventory supply is

$$\alpha_{23} \equiv \theta^s = -\eta^u \frac{Q^u}{I}. \tag{16}$$

The ratio of inventory to use never exceeded 0.4 in our sample period, and it would seem reasonable to suppose that the elasticity of demand for current use exceeds 0.1 in absolute value. Thus, we place a lower bound of $0.1/0.4=0.25$ on α_{23}. The α_{32} inverse elasticity in our econometric specification reflects the potential net response of next-period's producers and consumers to expected prices. This elasticity should be at least as large as the short-run elasticity of current-period net supply with respect to the current price because firms are at least as able to respond to current shocks during the next period as they are during the current period. Thus, we place an upper bound of $1/\alpha_{32}$ on α_{23}, and we have $0.25 \le \alpha_{23} \le 1/\alpha_{32}$.

To summarize, we impose three assumptions:

(i) Short-run elasticity of demand for current use exceeds -0.1 in absolute value.

(ii) Inventory-to-use ratio never exceeds 0.4, which is the sample maximum.

(iii) Elasticity of next year's net supply is not less than elasticity of current net supply.

Together, these assumptions imply $0.25 \le \alpha_{23} \le 1/\alpha_{32}$, and based on the estimates of Adjemian and Smith (2012), we further expect $\alpha_{23} \approx 4.4-1/\left(\alpha_{32}(1+\alpha_{43})+\alpha_{42}\right)$. Proceeding under these assumptions, we estimate the model parameters using data from

1961 to 2005. Based upon the estimated parameters, we forecast prices and inventory for the period from 2006 to 2011 and conduct a counterfactual experiment to assess the impact of expanding ethanol production.

4.3. Counterfactual Analysis

We forecast prices and inventory under various assumptions regarding the structural shocks U_t. First, we set the inventory-demand shock to zero for 2006–11 and set the remaining shocks to their values implied by the parameter estimates. This experiment predicts the prices that would have occurred if the market had experienced the same real-economic-activity, inventory-supply, and supply-of-storage shocks as in fact occurred but had not been hit by any inventory-demand shocks. Specifically, we generate

$$\begin{bmatrix} REA_t^{CF} \\ i_t^{CF} \\ f_t^{CF} \\ cy_t^{CF} \end{bmatrix} = \hat{A}^{-1}\hat{B}\begin{bmatrix} REA_{t-1}^{CF} \\ i_{t-1}^{CF} \\ f_{t-1}^{CF} \\ cy_{t-1}^{CF} \end{bmatrix} + \hat{A}^{-1}\hat{\Gamma}Z_t + \hat{A}^{-1}\begin{bmatrix} \hat{u}_{1t} \\ \hat{u}_{2t} \\ 0 \\ \hat{u}_{4t} \end{bmatrix},$$

where $\hat{A}$, $\hat{B}$, and $\hat{\Gamma}$ denote estimates of the structural parameters and $\hat{u}_t$ denotes the structural residuals. If all inventory-demand shocks emanate from changes to expected future ethanol demand, then the difference between the observed and counterfactual variables provides an estimate of ethanol's effect on prices and inventory. This effect operates through the inventory-demand channel. The absence of inventory-demand shocks would imply that the market did not display the foresight to hold inventory to meet the impending ethanol-demand boom. In that case, we would expect inventories to be drawn down as ethanol use increased, but prices would not rise as much as they would have done if the market were demanding more inventories in anticipation of future ethanol production.

As Figure 3 shows, permanent increases in ethanol production shift the inventory-supply curve to the left and the inventory-demand curve to the right. In our second experiment, we set both the inventory-demand (u_{3t}) and inventory-supply shocks (u_{2t}) to zero for 2006–11. This experiment produces an estimate of the effect of ethanol production on corn prices under the assumption that no other inventory demand or supply shocks affected the corn market in 2006–11.

Although the years 2006–11 did not produce extreme Corn Belt weather events (such as occurred in 1983, 1988, and 2012), corn production did fluctuate significantly during this period. In our third counterfactual experiment, we allow for inventory-supply shocks from surprises in the US corn harvest. To measure these surprises, we use the difference between actual production and the World Agricultural Supply and Demand Estimates (WASDE) that are made in May of each year. The May WASDE report is the first one released in each crop year. It is based on a survey of planted acreage and projected trend yield. Production in 2007 and 2009 exceeded expectations by 5 and 8 percent, respectively, whereas production in 2010 and 2011 was 7 and 8 percent, respectively, below expectations. To incorporate these surprises in our counterfactual scenario, we generate

$$\begin{bmatrix} REA_t^{CF} \\ i_t^{CF} \\ f_t^{CF} \\ cy_t^{CF} \end{bmatrix} = \hat{A}^{-1}\hat{B}\begin{bmatrix} REA_{t-1}^{CF} \\ i_{t-1}^{CF} \\ f_{t-1}^{CF} \\ cy_{t-1}^{CF} \end{bmatrix} + \hat{A}^{-1}\hat{\Gamma}Z_t + \hat{A}^{-1}\begin{bmatrix} \hat{u}_{1t} \\ \delta_t \\ 0 \\ \hat{u}_{4t} \end{bmatrix}, \tag{17}$$

where $\delta_t = \ln(1 + S_t / 40)$ and S_t denotes the production surprise in year *t*, which we measure in millions of metric tons. We standardize by the average inventory in each of the last 10 years of our estimation sample, which was 40 million metric tons. By using this functional form for δ_t, we allow a linear shift of magnitude S_t in the quantity of inventory supplied.

5. Results

5.1 Parameter Estimates and Impulse Responses

Table 1 contains the reduced-form parameter estimates[19] and estimates of the structural-parameter matrix *A*. Both the BIC and the small-sample corrected AIC of Hurvich and Tsai (1989) indicate that a model with a single lag is the most favored model. The first three variables in the system have significant autocorrelation, and estimates of the coefficient on the lagged dependent variable equal about 0.6 in each case. These estimates are far below the threshold for a unit root, which is consistent with the apparent mean-reverting behavior of these variables in Figure 4. The convenience-yield variable produces a coefficient of 0.27 on its lag, but this estimate is not statistically significant. The first three variables also display statistically significant trends: real futures prices and REA trend down and inventory trends up.

If we fix α_{23} based on the assumption that $\theta^s - \theta^d = 4.4$ (as suggested by the discussion in Section 4.2), then the estimated short-run elasticity of inventory supply equals 1.82. Under this same assumption, the estimated short-run elasticity of inventory demand

[19] The reduced-form parameters correspond to $A^{-1}B$ in (9) and are estimated by OLS.

equals -1/0.21=-4.85. Thus, the short-run inventory-demand elasticity is substantially greater than the short-run inventory-supply elasticity; this proposition is consistent with the notion that next year's net demand is more elastic than this year's net demand. Constraining our parameters only to lie in the identified set produces a range from 4.07 to 0.25 for α_{23}. The lower bound implies $\theta^s - \theta^d = 3.31$, and the upper bound implies $\theta^s - \theta^d = 6.48$. As we show in subsequent sections, this wide range has little effect on our price-impact results, but it has larger effects on our counterfactual predictions of inventory. The range for the elasticity of inventory demand is narrower; it spans from -1/0.17=-5.88 to -1/0.25=-4.00. The supply-of-storage parameters are largely unaffected by changes in θ^s.

Figure 5 shows impulse-response functions. The box in the figure signifies the identified set, and the vertical lines above and below indicate confidence intervals with greater than 90 percent coverage.[20] A real-economic-activity shock raises futures prices significantly for several years. In contrast, it lowers inventory and convenience yield by statistically insignificant amounts. Lower convenience yield signifies an increased demand for inventory, so the signs of these responses are consistent with the supposition that these demand shocks elevate both current and future demand.

[FIGURE 5 HERE]

[20] We generate confidence intervals using a recursive-design wild bootstrap with 10,000 replications (Goncalves and Kilian 2004). For each bootstrap draw, we estimate the identified parameter set and the range of impulse responses defined by that set. This exercise produces 10,000 bootstrap draws for both the estimated lower and upper bounds of the identified set. We set the lower limit of the confidence interval equal to the 0.05 quantile across draws of the estimated lower bound and the upper limit as the 0.95 quantile across draws of the estimated upper bound. This interval covers the identified *set* with probability 0.90, because 90 percent of the estimated parameter sets lie entirely inside it. Imbens and Manski (2004) show that the confidence interval for the identified *set* is wider than the confidence interval for the true *parameter* within the set. Heuristically, this result follows from the fact that the true parameter (a single point within the identified set) necessarily covers a narrower range than the identified set (assuming that the set has positive measure). Thus, a 90 percent confidence interval for the whole set covers the true parameter with probability greater than 0.90.

Inventory-supply shocks raise inventory levels and lower the futures price and convenience yield (as would be expected from Figures 2 and 3). Inventory-demand shocks generate a greater range of responses within the identified set, which is consistent with the wide range of α_{23}. These shocks raise inventory levels over several years, and they also raise futures prices accordingly. The convenience-yield response to inventory demand is negative, as expected. Consistent with Figures 2 and 3, a positive supply of storage shock (increasing convenience yield) implies a shift downward in the supply-of-storage curve and an increase in inventories. Overall, the impulse responses are consistent with our theory.

5.2 Historical Decomposition and Counterfactual Analysis

Figure 6 shows a historical decomposition of the four variables for the case with $\theta^s - \theta^d = 4.4$. The decomposition reveals the cumulative contribution of each of the four shocks to the observed variable. It shows that most of the variation in inventory emanates from inventory-supply shocks, as expected. However, substantial increases in inventory demand occurred in 2006–11. Futures prices are affected strongly by real economic activity, which produced high prices in the 1970s and again in the most recent decade. However, inventory demand contributed significantly to prices in 2006–07 and again in 2010-11. Inventory-supply shocks affected prices in several episodes, including 2010 and 2011. In these two years, respectively, actual production was 7 and 8 percent below expectations due to below-average weather during the growing season. Convenience yield is driven mostly by inventory supply, which would be expected from a relatively constant supply-of-storage curve that we slide up and down as inventory levels change. Inventory demand dampens convenience yield in the 2006–11 period.

[FIGURE 6 HERE]

To further explore the effect of the various shocks and draw implications for the effect of ethanol production on corn prices, we conduct the counterfactual analysis that we introduced in Section 4.3. Figure 7 shows these results for $\theta^s - \theta^d = 4.4$, and Table 2 shows the ranges implied by the identified set. If there had been no inventory demand shocks in 2006–11, inventory would have dropped precipitously, as shown by the green line in Figure 7. The first row of Table 2 shows that inventory levels were 59 percent higher in log terms, on average, than they would have been in the absence of realized inventory-demand shocks. In other words, the market responded to the growth in ethanol production by holding more corn in inventory than it otherwise would have. This inventory demand caused prices to increase by 20 percent, on average, over the six-year period, and it lowered the convenience yield by 5 percent, on average. This result supports the hypotheses of Figure 2: an increase in inventory demand raises the demand for storage and therefore increases the price of storage, i.e., an increase in inventory demand affects cash prices less than it does futures prices. This result reinforces the findings of Garcia, Irwin and Smith (2012), who show significant decreases in convenience yield since 2006.

[FIGURE 7 HERE]

The dominant net-supply shock during 2006–11 was the growth of the ethanol industry. The red line in Figure 2 shows the counterfactual case of no inventory supply or demand shocks between 2006 and 2011. The green line indicates lower inventory and higher prices than the red line because it includes the increased current-use demand for corn. In other words, the growth in ethanol use caused inventory to be run down and prices to rise. Table 2 shows that, on average over the six years, cash prices were 34 percent greater and futures prices were 35 percent greater than they would have been in the absence of inventory-supply or inventory-demand shocks. But note that this counterfactual price is still 16 percent greater, on average, than the 2005 price. We deduce that strong global growth is responsible for about a third of the average corn-price increase since 2005, and corn supply and demand is responsible for the other two-thirds.

In normal times, annual price variation is dominated by weather shocks that affect crop yield. No major weather events occurred in the Corn Belt during the 2006-11 period; nevertheless, in any given year, production still differed by up to 8 percent from expectations. The blue line in Figure 7 shows counterfactual paths that assume no inventory-demand shocks and limit net-supply shocks to those that derived from US production surprises. Incorporating production shocks does change the path of prices and inventory, but it has little effect on the average difference between the actual and counterfactual values. The reason for this is that production shocks are temporary; the large crop in 2009 was offset by small crops in 2010 and 2011. The ethanol boom, in contrast, is permanent. In summary, based on this counterfactual, we estimate that ethanol production raised corn prices by 30 percent, on average, between 2006 and 2011.

Our analysis reveals not only the average price differences but also the dynamic responses of prices and inventory to the ethanol boom. Corn prices jumped 26 percent in 2006–07 and increased further in 2007–08, mainly because demand for inventory was high. In late 2008, the financial crisis and the corresponding crash in oil prices and gasoline demand caused a drop in demand for corn from ethanol producers. The counterfactual analysis shows that in the following two years, the effect of ethanol demand on corn prices was much more moderate. However, the 2010 revival in oil prices made ethanol profitable again. Along with the worse-than-expected crops in 2010 and 2011, this oil-price increase caused prices to rise again significantly above the counterfactual values. In these last two years, we estimate that corn prices were 45 and 38 percent greater than they would have been without the ethanol-induced shocks.

Finally, the counterfactual implications for prices depend little on the fact that our model is set- rather than point-identified. Based on the identified set, we estimate the average price effect to be between 31 and 32 percent for futures prices and between 29 and 31 percent for cash prices. Inventory, however, is much more sensitive to the location of our parameters in the identified set. Our estimated inventory effect ranges from 15 to 21 percent across the identified set; this wide range is generated by the range of α_{23}.

5.3 The 2012 Drought

In this section, we perform a counterfactual analysis of the drought that gripped the Midwestern United States in June and July of 2012. The drought is widely reported to be the worst in at least 50 years. At the time of writing, we do not have data to perform the counterfactual analysis in Section 5.2. We use mid-crop-year prices in our analysis, which will be observed for the 2012 crop year in March 2013 and crop-year-ending inventories, which will be observed at the end of August 2013. However, using futures prices and USDA projections, we can provide some insight into the likely effects this drought would have had in the absence of the RFS.

After poor crops in 2010 and 2011 caused inventory to run down and prices to increase, planted corn acreage increased by 5 percent in 2012. The crop was planted in the late spring, and in May the USDA projected that production would be sufficient to enable the United States to exit the 2012 crop year with more than twice as much inventory as the amount with which it began. However, hot and dry weather caused the USDA projected yield to drop from 166 bushels per acre in May to 123 bushels per acre in August. This 26 percent drop in expected production caused corn prices to rise from $5.00 per bushel in May to $8.00 in August.

Between May and August, expected 2012 corn production declined by 102 million metric tons, which is 2.5 times the average inventory level of 40 million metric tons that we use in our counterfactual simulation in Section 5.2. We took the 2011 counterfactual values (as generated from equation [17]) from Table 2, set the production shock δ_t to -2.5, set the as yet unobserved REA and convenience yield shocks to zero, and projected forward to 2012. We compared the resulting projections to the latest available forecasts of the 2012 values. Specifically, we use USDA's August estimate of crop-year-ending 2012 inventory (16,500 million metric tons) and the Chicago futures prices on September 5 for March 2013 delivery ($7.95) and December 2013 delivery ($6.56).[21] Our counterfactual futures price was 45 percent below the expected futures price and 38 percent below the expected cash price. Counterfactual inventory was 64 percent below USDA's inventory prediction and the counterfactual convenience yield was 7 percent greater than what we currently expect

[21] We also assumed that interest rates and inflation were the same in 2012 as in 2011.

based on futures prices. Both inventory and convenience yield jump to the levels observed in 1995, which was the year of the most recent poor harvest.

These counterfactual projections show that, in the absence of the ethanol shocks observed since 2006, this drought would have caused inventory to decline by significantly more than USDA projects that it will. This difference comes from inventory demand; in the counterfactual world without ethanol, the market would choose to run down inventory and replenish it the following year. In the world we live in, which has a large component of permanent inelastic demand for corn from ethanol producers, the willingness to hold inventory is higher. The poor 2010 and 2011 harvests mean that inventories would have been low entering this year even without ethanol production, as shown by the blue line in Figure 7. Thus, our counterfactual price effects are quite similar to those in 2010 and 2011 at about 40 percent, although due to inventory demand, the futures price is affected more than the spot price.

6. Corroborating Evidence

In this section, we present three pieces of evidence that reinforce the empirical results described in Section 5. First, we investigate the spatial behavior of prices; second, the potential causal influence of commodity speculation; and third, the financial economics of ethanol-processing plants.

6.1 Spatial Price Differences

Grain-price differences across space reflect transportation costs and the geographic flow of grain (Brennan, Williams, and Wright 1997). Prices are typically lowest in producing regions and highest at ports. For corn, in the United States, this means that prices are typically lower in Illinois and Iowa than they are in locations on the Mississippi River such as St. Louis or Memphis. In turn, prices in St. Louis or Memphis are typically lower than they are on the Louisiana Gulf. Iowa and Nebraska each produce more ethanol than any other state; these two states lie in the western Corn Belt. The rise of local ethanol production in the western Corn Belt means that much less corn flows out of these states than was once the case. As a result, the relative price of corn in Iowa, where more ethanol production facilities exist, to the price in Illinois, where fewer ethanol production facilities exist, jumped in 2006 and has remained high since that time. Although Illinois and Iowa are the two largest corn-producing states, they have experienced markedly different levels of investment in ethanol plants.

In 2010, Iowa comprised 17 percent of the US corn harvest and 27 percent of corn-ethanol production. Furthermore, Iowa produced twice as much ethanol as the next-highest corn-ethanol-producing states, Illinois and Nebraska. In Iowa, corn used in ethanol production totaled 62 percent of the harvest, compared to 28 percent in Illinois. In contrast, relative production of corn itself in the two states has changed little over time. On average, between 1980 and 2005, Iowa produced 13 percent more corn than Illinois; between 2006 and 2011, Iowa produced 11 percent more. Because Illinois is closer to the Louisiana Gulf, through which most corn exports flow, corn prices in Illinois were 6.6 percent higher, on average, than they were in Iowa before 2005. Figure 8 shows no discernible trend in this relative price between 1960 and 2005. Moreover, Figure 8 shows that in the early 2000s, these two states had very similar ethanol-production capacity, namely, 700 million gallons per year.[22]

[FIGURE 8 HERE]

In 2006, a building boom caused current and under-construction ethanol-production capacity in Iowa to double, from 1,700 to 3,200 million gallons per year. During that same year, Illinois' capacity expanded more moderately, from 900 to 1,200 million gallons per year. Again in the same year, the relative price jumped significantly in Iowa's favor and remained at the new level; from 2006 through 2011, Iowa prices exceeded Illinois prices by 1.3 percent, on average. In each of those 6 years, the relative price exceeded its highest value in any of the previous 46 years. This large swing in relative prices was clearly driven by the ethanol expansion in Iowa, and the timing coincides with our results in Section 4.

6.2 Financial Speculation

Commodity prices rose and fell dramatically in the latter half of the 2000s (Carter, Rausser, and Smith 2011). Kilian (2009) demonstrates that strong global demand for commodities explains much of the rise in crude-oil prices, a result largely replicated by our analysis for corn. Other factors, such as macroeconomic linkages and supply shocks, also contributed to the boom and bust (Carter, Rausser, and Smith 2011).

In addition to such fundamental factors, many commentators have suggested that the rise of financial speculation in commodities was a factor in the price boom and bust. Commodity index funds have received particular attention (Irwin and Sanders 2011). These

[22] The two ethanol-production-capacity curves in Figure 8 represent the sum of operating capacity and capacity under construction.

funds take positions only on the long side of the market. Obviously, if traders on the short side of the market were unable to accommodate the increased demand for long futures positions, futures prices would rise. Because index funds follow a well-defined trading strategy that is announced publicly, such a lack of liquidity on the short side would emanate from limits to arbitrage rather than from surprise (DeLong et al. 1990). If futures prices were to rise, there would be a greater incentive to store corn for future sale at a high price. This increased inventory demand would pull spot prices higher. In short, if a derivatives price change is to affect the price of the underlying commodity, then there should be a quantity change in the form of increased inventory (Hamilton 2009). An exception could occur only if demand for the commodity were perfectly inelastic, a relationship that does not exist in the case of corn (Adjemian and Smith 2012).

Could the inventory-demand shock that emerged in 2006 have resulted from financial speculation? Substantial evidence suggests that this is unlikely. First, index-fund participation in corn futures increased rapidly in 2005, a full year before prices and inventory demand increased. If futures markets could absorb the influx of capital in 2005, then it would seem likely they could do so in 2006. Second, numerous authors (including Irwin, Sanders, and Merrin 2009; Irwin and Sanders 2011; and Stoll and Whaley 2010) have tested empirically the assertion that commodity index fund positions Granger cause corn prices to rise but found no evidence supporting that hypothesis. Third, if the corn-price jump in 2006–07 reflected index-fund activity, then this price jump should have coincided with a similar price jump for other commodities in which index funds hold positions. Figure 9 shows real prices for four major commodities, including corn. It shows the corn-price jump in the fall 2006, but none of the other commodities reveals a similar pattern. Copper jumped in late 2005 and early 2006, and cotton moved little until supply shortages occurred in the fall of 2010. Crude oil prices decreased in fall 2006, when corn prices first increased, and then increased again in mid-2007. These price patterns do not suggest that a broad speculation drove corn-inventory demand to increase in the fall of 2006.

[FIGURE 9 HERE]

6.3. Ethanol Refining Margin

Figure 10 shows the price of ethanol per gallon since January 1998, decomposed into its main cost components. A bushel of corn produces about 2.8 gallons of ethanol and 17 pounds of dried distiller's grains (as noted earlier, these grains are used as animal feed). The refining process uses about 0.0728 million Btu of natural gas per bushel of corn. Following the Center for Agricultural and Rural Development at Iowa State University,[23] we set "other operating costs" at $0.35 per gallon and add this amount to the costs of the corn and natural gas that are used in production. The light-gray component of the graph, which we label "net returns," represents the difference between the ethanol price and the sum of the three cost components.

[FIGURE 10 HERE]

Prior to the fall of 2006, ethanol prices far exceeded the three cost components during three periods: 2000–01, 2004, and 2005–06. Most notably, ethanol prices spiked during Hurricane Katrina, in August 2005, and then reached an even higher peak in mid-2006. This 2006 spike was caused partly by a supply crunch generated by the legislated

[23] http://www.card.iastate.edu/research/bio/tools/hist_eth_gm.aspx

phase-out of MTBE as a fuel additive (Dahlgran 2009). Neither these spikes nor those in 2001 and 2004 were strongly associated with corn prices.

Net returns to ethanol production dropped sharply when corn prices rose in fall 2006, settling at $0.70 per gallon until mid-2007. Since August 2007, net returns have held steady at $0.35 cents per gallon. As we found in Section 5, the 2006 jump in corn prices emanated from an increase in inventory demand: firms chose to store more corn in anticipation of selling it when future ethanol production expanded. Thus, large returns to ethanol production persisted until mid-2007, when sufficient capacity existed to drive profits downward. Mallory, Hayes, and Irwin (2011) show that during this interim period (fall 2006 to summer 2007), one-year-ahead futures prices implied zero expected profit in ethanol production. Thus, although the spot price of ethanol remained high relative to corn during this period, future corn and ethanol pricing were integrated. These authors show, further, that this pricing relationship did not exist prior to fall 2006. As a result, changes in the ethanol-refining margin over time imply that ethanol demand began to affect the price of corn materially in the fall of 2006.

7. Conclusion

In this paper, we have measured the relationship between US ethanol expansion and corn prices. The United States expanded its ethanol production capacity almost fourfold between 2005 and 2011, from 3.9 to 13.9 million gallons per year. Over the same period, the number of ethanol plants more than doubled, from 81 to 204. We use structural vector autoregression to model corn-inventory dynamics and use a counterfactual experiment to estimate what prices would have been in the absence of ethanol-induced shocks to inventory supply and demand.

We isolate three main results that have not been previously quantified in the literature. First, the corn market anticipated the forthcoming ethanol boom and increased inventory demand accordingly. As a result, prices increased in 2006 in advance of the ethanol-production jump in 2007 and 2008. Second, we estimate that on average, corn prices would have been 30 percent lower from 2006 through 2011 if ethanol producers had not increased their demand for corn. Our third finding is that below-average harvests in 2010 and 2011 caused inventory to be run down and prices to be about 40 percent higher than they would have been if ethanol production had been frozen at 2005 levels. These two years also placed food markets on a knife's edge going into the 2012 crop year. In early 2012, the US Department of Agriculture (USDA) forecast that corn inventories could dwindle to 5 percent of annual use before the 2012 harvest, the smallest fraction since the Great Depression.

Since the end of our estimation sample, the US Corn Belt has experienced a devastating drought. Because inventories had reached such low levels, the price effects have been dramatic. In August, the USDA projected that the harvest would be 26 percent below its pre-drought projection. As a result, corn prices increased by 60 percent between June and August of 2012. We estimate that, after this price rise, corn prices were about 40 percent above where they would have been if ethanol production had been frozen at 2005 levels. The RFS requires that 13.2b gal of corn-ethanol be produced in 2012, which now corresponds to about 35 percent of expected US corn production (after accounting for distiller's grains). Thus, the RFS places a high minimum on ethanol production, especially when combined with the expanding biofuel mandates around the world (Ziolkowska et al., 2010). At the time of writing, this inelastic component of ethanol demand is elevating corn prices dramatically and directly contributing to another serious international food crisis.

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Table 1: VAR Parameter Estimates

Equation	*REA*	*Inventory*	*Futures*	*Conv. Yield*
		Reduced Form Estimates: $A^{-1}B$		
$REA_{t\text{-}1}$	0.626* (0.133)	-0.692 (0.409)	0.233 (0.140)	0.022 (0.061)
$Inventory_{t\text{-}1}$	-0.060 (0.055)	0.643* (0.180)	0.003 (0.053)	0.019 (0.029)
$Futures_{t\text{-}1}$	-0.279* (0.141)	0.817 (0.439)	0.604* (0.120)	-0.047 (0.064)
$Conv.\ Yield_{t\text{-}1}$	-0.081 (0.344)	1.000 (0.794)	0.016 (0.378)	0.272 (0.177)
Constant	1.090 (0.757)	2.130 (2.491)	0.595 (0.719)	0.015 (0.386)
Trend	-0.008* (0.004)	0.027* (0.011)	-0.012* (0.004)	-0.001 (0.002)
		A Matrix: imposing $\theta^s - \theta^d = 4.4$		
REA	1	0	0	0
Inventory	0.86	1	-1.79	-1.79
Futures	-0.41	0.22	1	0
Conv. Yield	0.06	0.14	0.14	1
		A Matrix: Identified Set		
REA	1	0	0	0
Inventory	[0.31,1.67]	1	[-4.03, -0.25]	[-4.03, -0.25]
Futures	[-0.42,-0.40]	[0.18,0.25]	1	0
Conv. Yield	[0.06,0.07]	[0.13,0.14]	[0.12,0.15]	1
		A Matrix: >90% Confidence Interval		
REA	1	0	0	0
Inventory	[-0.79,3.38]	1	[-6.03, -0.25]	[-6.03, -0.25]
Futures	[-0.63,-0.17]	[0.09,0.35]	1	0
Conv. Yield	[-0.06,0.24]	[0.06,0.19]	[-0.05,0.34]	1

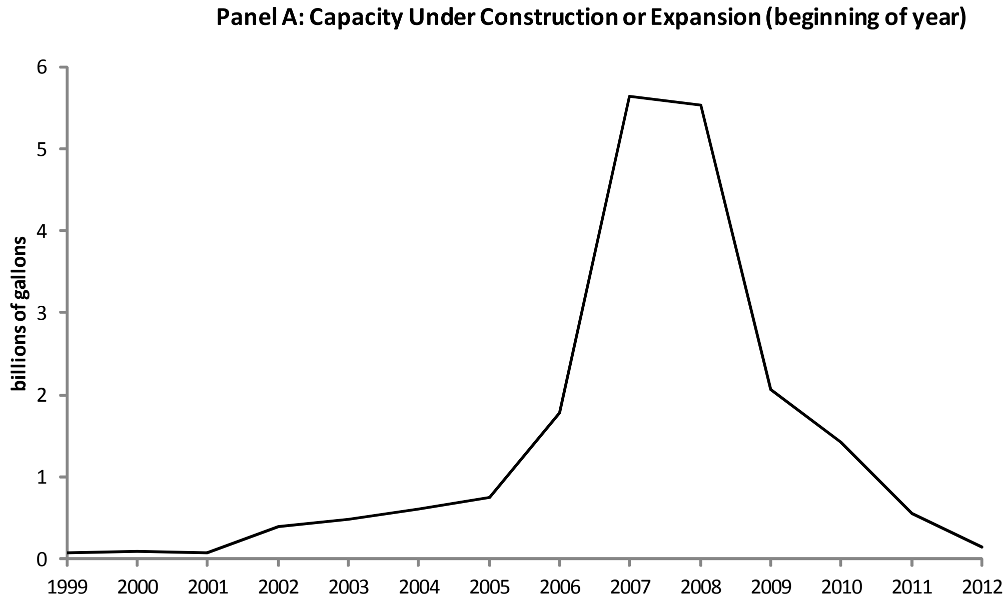
Notes: Sample range: 1961–2005; standard errors in parentheses; * indicates significance at 5%; model selection criteria values are AIC_C=-687.29 and BIC=-666.97; for the two-lag model, we obtain AICc = -669.66 and BIC = -639.40, so the one-lag model is favored. We obtain the confidence intervals using a recursive-design wild bootstrap (see footnote 20).

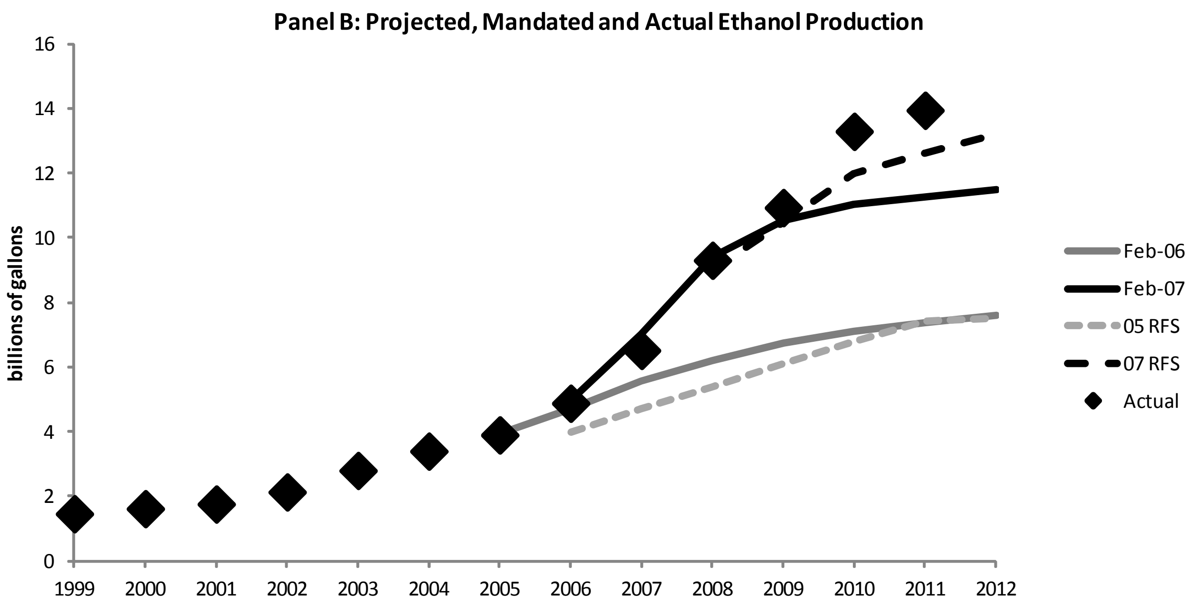
Table 2: Log Difference between Actual and Counterfactual

	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	Average
No Inventory-Demand Shocks							
Inventory	0.25	0.54	0.49	0.48	0.89	0.91	0.59
Fut. Price	0.20	0.35	0.11	0.00	0.34	0.24	0.21
Conv. Yield	-0.06	-0.09	-0.01	0.01	-0.11	-0.05	-0.05
Cash Price	0.14	0.25	0.11	0.01	0.23	0.19	0.16
No Inventory-Demand or -Supply Shocks							
Inventory	-0.12	0.30	0.46	0.42	-0.18	-0.59	0.05
Fut. Price	0.28	0.42	0.14	0.03	0.59	0.63	0.35
Conv. Yield	-0.02	-0.08	-0.02	0.01	0.00	0.07	-0.01
Cash Price	0.26	0.34	0.12	0.04	0.59	0.69	0.34
No Inventory-Demand Shocks							
Inventory-Supply Shocks from Production Surprises Only							
Inventory	-0.12	0.11	0.40	0.09	0.27	0.40	0.19
Fut. Price	0.28	0.46	0.16	0.11	0.51	0.40	0.32
Conv. Yield	-0.02	-0.06	-0.02	0.04	-0.06	-0.03	-0.02
Cash Price	0.26	0.40	0.15	0.15	0.45	0.38	0.30
Identified Set							
No Inventory-Demand Shocks							
Inventory-Supply Shocks from Production Surprises Only							
Inventory	[-0.12,-0.10]	[0.00,0.20]	[0.27,0.48]	[-0.17,0.26]	[0.12,0.47]	[-0.02,0.77]	[0.15,0.21]
Fut. Price	[0.28,0.28]	[0.44,0.47]	[0.14,0.19]	[0.07,0.15]	[0.50,0.53]	[0.36,0.45]	[0.32,0.32]
Conv. Yield	[-0.03,-0.02]	[-0.06,0.05]	[-0.02,-0.01]	[0.03,0.05]	[-0.10,-0.02]	[-0.07,0.03]	[-0.04,-0.01]
Cash Price	[0.25,0.27]	[0.38,0.41]	[0.12,0.17]	[0.10,0.21]	[0.40,0.50]	[0.29,0.48]	[0.29,0.31]
Production Surprises (MMT)							
Actual Prod.	267.50	331.18	307.14	332.55	316.17	313.92	
May Forecast	267.98	316.50	307.99	307.10	339.61	343.04	
Surprise	-0.48	14.68	0.85	25.45	-23.45	-29.12	

Note: Here we define the log cash price as f_t+cy_t.

Figure 1: Growth of the Ethanol Industry





Data Sources: USDA baseline projections, Renewable Fuels Association Annual Industry Outlook, Energy Information Administration of the US Department of Energy.

Figure 2: Two-Period Commodity-Market Equilibrium

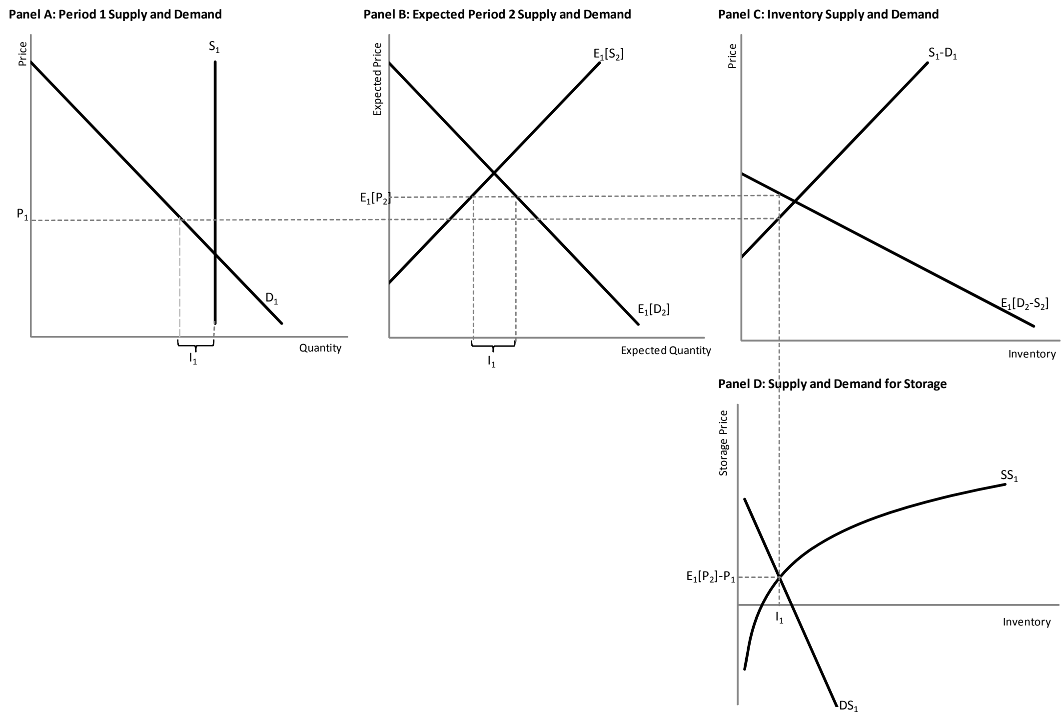


Figure 3: An Increase in Demand

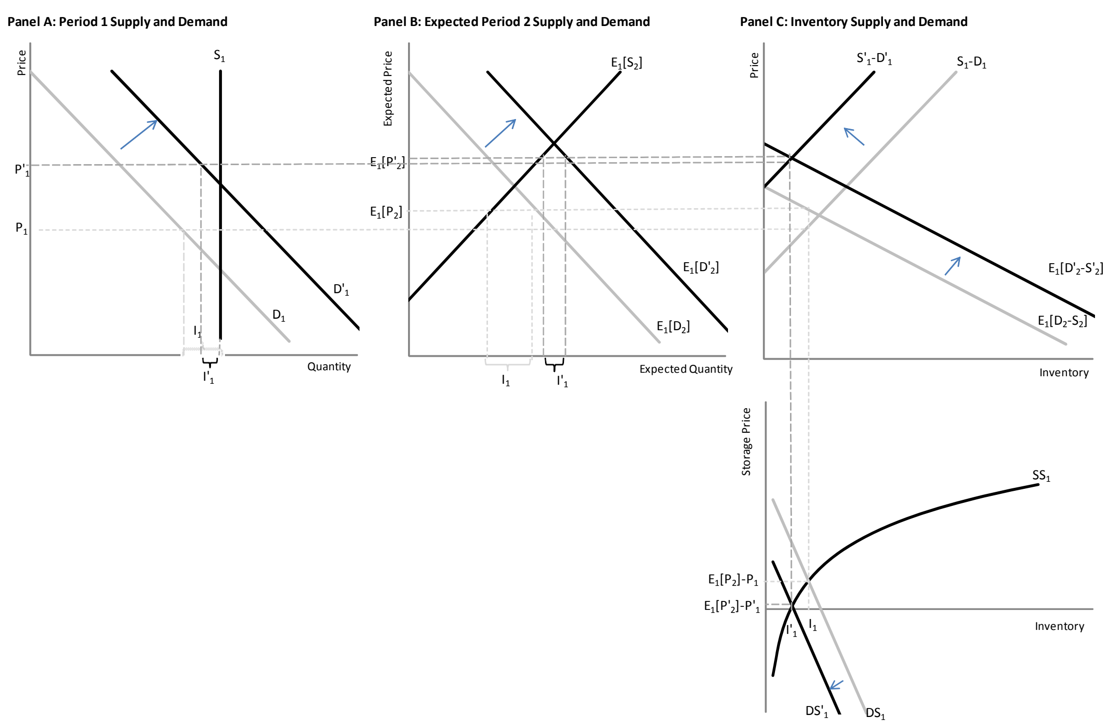
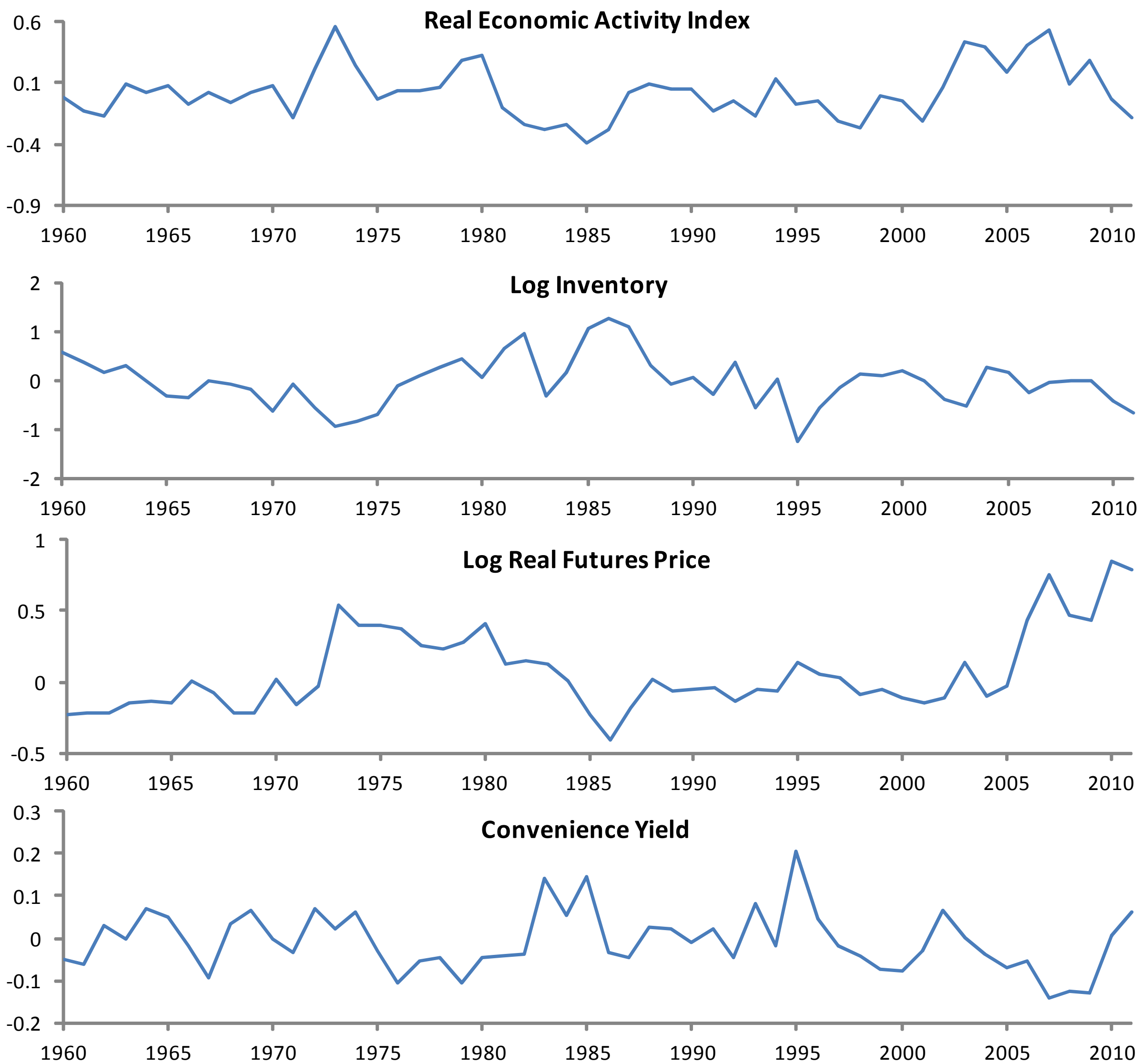
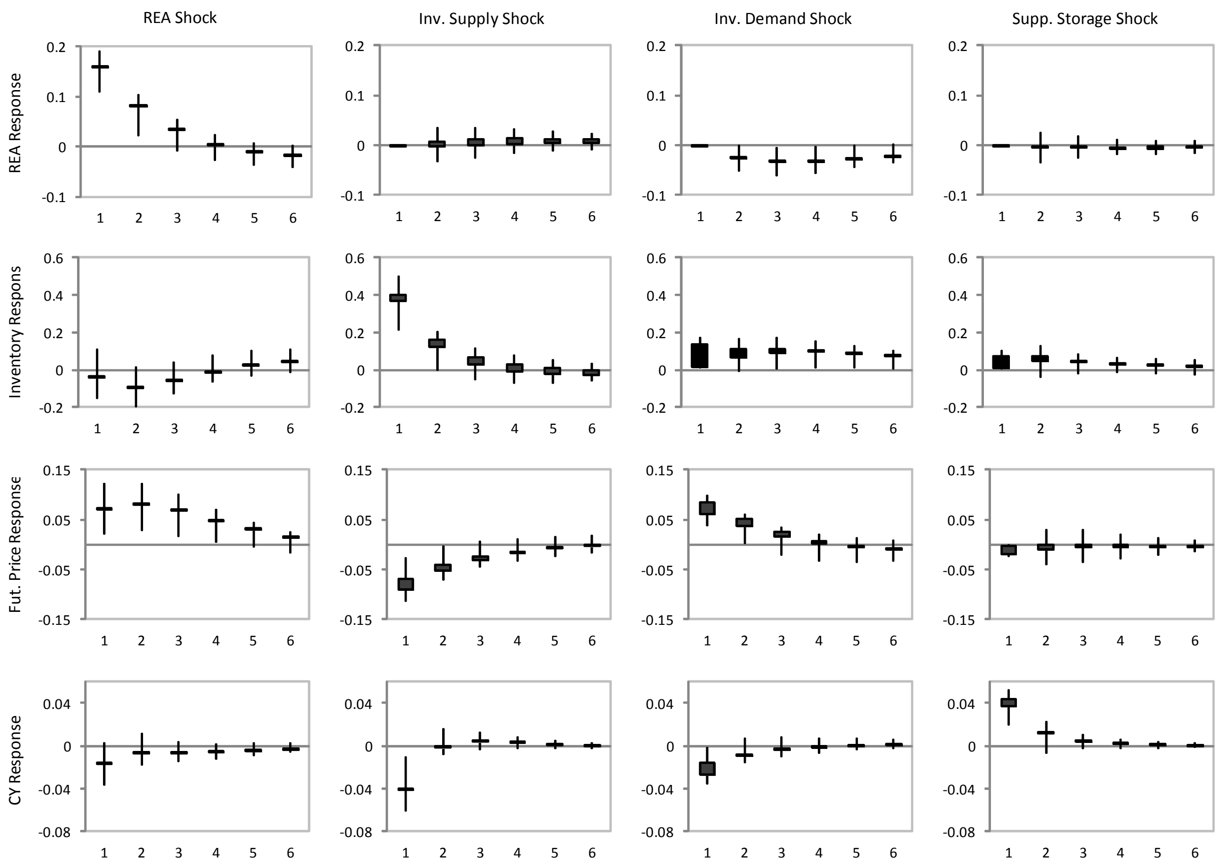


Figure 4: De-Trended Data for Key Variables



Note: For clarity, this figure shows linearly de-trended series. For the VAR estimation, we use the actual series and include a constant and linear trend in each equation of the model.

Figure 5: Impulse Responses



Note: The dark boxes indicate the range of impulse responses in the identified set. The vertical bars indicate estimated confidence intervals that cover the true parameter with probability greater than 0.90. We obtain these intervals using a recursive-design wild bootstrap (see footnote 20).

Figure 6: Historical Decomposition

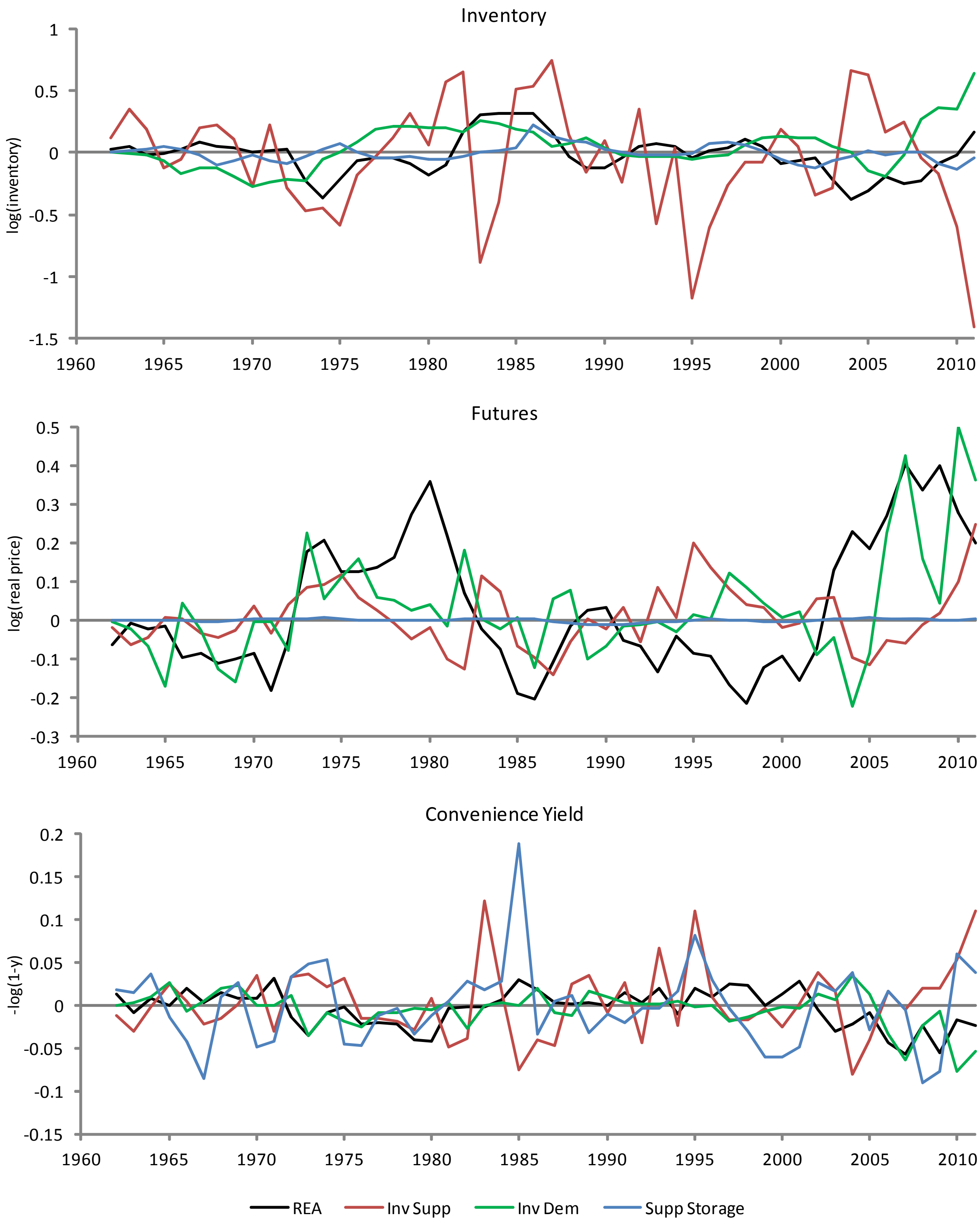


Figure 7: Counterfactual Analysis

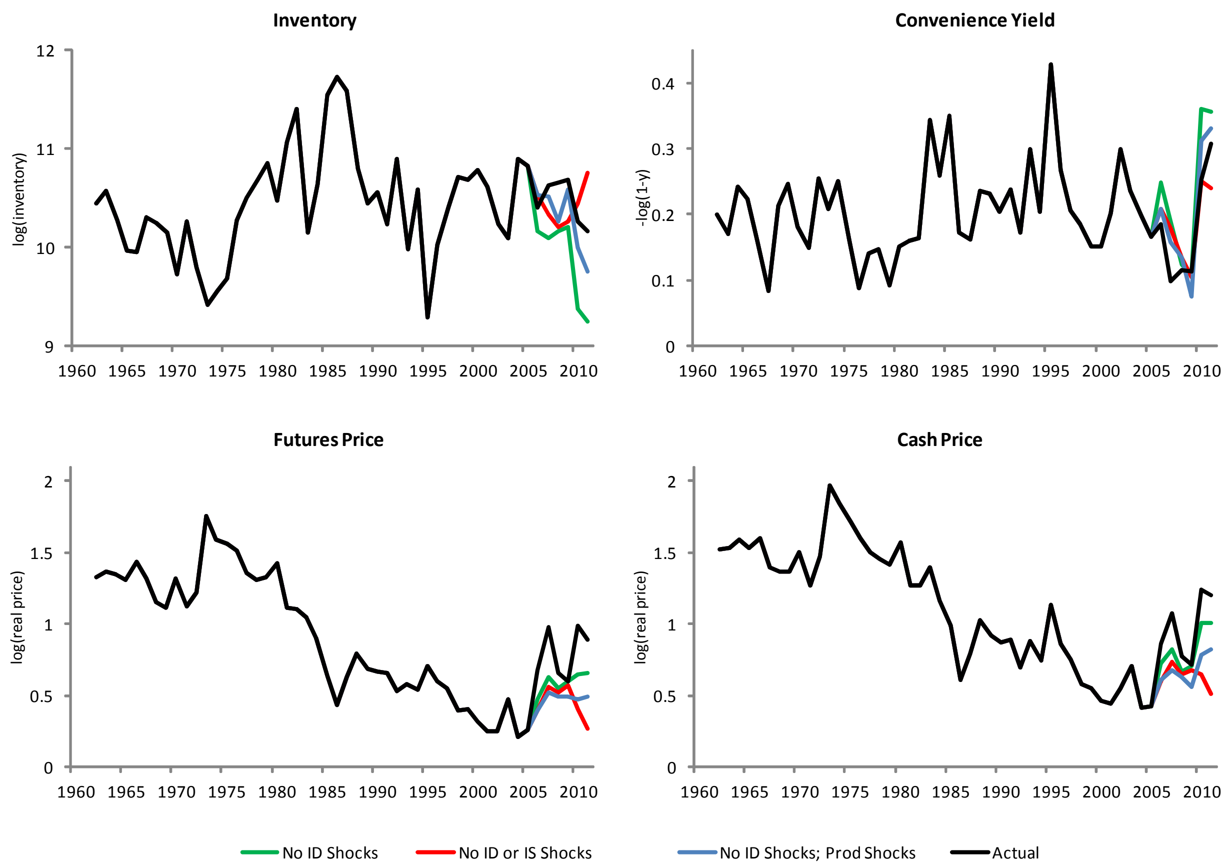


Figure 8: Relative December Corn Prices in Iowa and Illinois

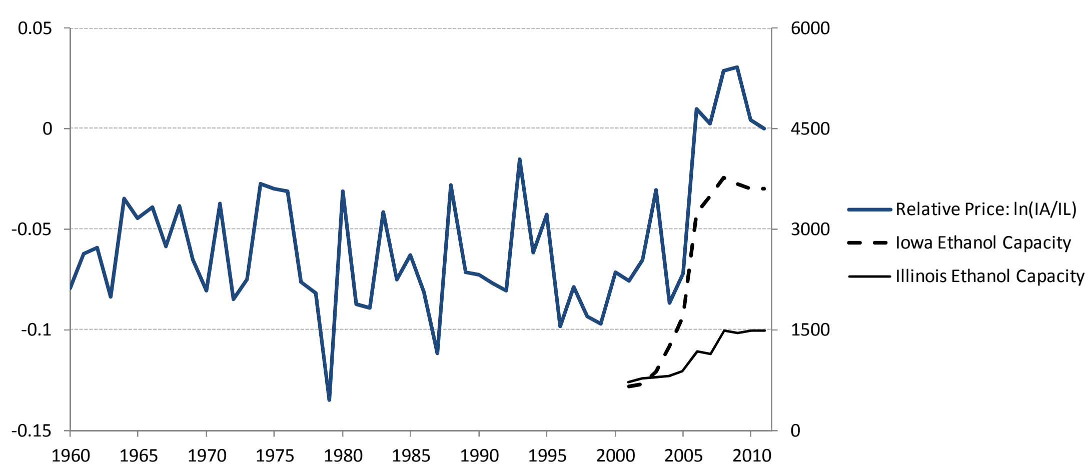


Figure 9: Real Prices of Four Major Commodities (Indexed to 100 in 2000)

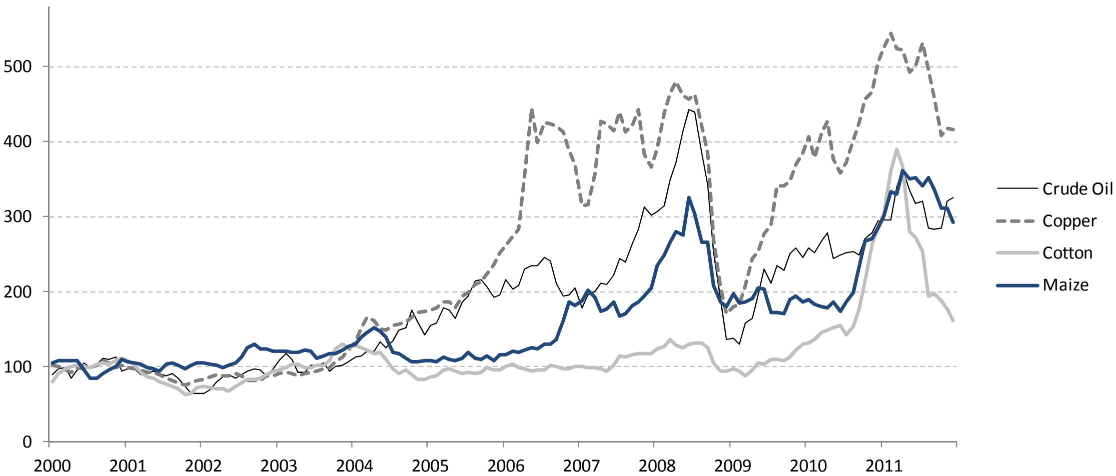


Figure 10: Ethanol Price Decomposed Into Cost Components