

Commodity Storage and the Market Effects of Biofuel Policies

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Abstract

US legislation passed in 2007 requires that 15 percent of the world's corn be used to make ethanol for fuel use. We estimate the price of corn but for this mandate. Using modern time-series methods, we estimate that corn prices were 34 percent higher between 2006 and 2012 because of the mandate. Our identification strategy is unique in the literature because it enables estimation of the effects of transitory shocks, such as weather, separately from the effects of persistent shocks, such as the ethanol mandate. This method applies not only to the ethanol mandate, but also to events in other markets.

Keywords: Ethanol; agriculture; energy policy; VAR; partial identification

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“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

More land is now planted with corn than with any other crop in the United States. In 2012, 40 percent of US corn was used to make ethanol to blend 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 partially identified structural vector autoregression that the 2007 expansion in the RFS caused a persistent 34 percent increase in global corn prices.

Ethanol production diverts a substantial amount of grain out of the food system. In 2012, 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 (about 85 million metric tons) is substantial: it exceeds total corn consumption in all of Africa and in any country other than China. By volume, it also exceeds 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 a major portion of the diet. According to the Food and Agriculture Organization (FAO) of the United Nations (2008), grains comprised 57 percent of calories consumed in least-developed

¹ Grains include wheat, corn, barley, sorghum, oats, rye, and rice. About 15 percent of the world’s corn was used to make ethanol in 2012. Since corn comprises one-third of world grain production about 5 percent of the world’s grain production was used to produce ethanol in 2012. 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/>.

countries in 2007 but only 22 percent in the United States and 27 percent in the European Union.² Ivanic, Martin, and Zaman (2011) estimate that when the World Bank's food-price index jumped by 30 percent in 2010, 44 million people were forced below the extreme poverty line of US \$1.25 per day.

Previous studies have found that corn-ethanol production affects corn prices. The International Food Policy Research Institute (IFPRI, 2008) and the OECD (2008) have both publicized reports claiming 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 the volatility (Wright 2011) of corn prices. But each of these papers is mainly qualitative; none provides rigorous empirical estimates to support its conclusions.

Two recent papers produce econometric estimates of the effect of ethanol production on agricultural markets. Hausman, Auffhammer, and Berck (2012) estimate a large factor-augmented vector autoregression of cropland allocation in the US. They calculate that removing land from food production to produce corn for ethanol raised corn prices in 2007 by \$0.24 per bushel (less than 10%). Roberts and Schlenker (2013) estimate the elasticities of world supply and demand for calories from storable agricultural commodities. They create a calorie-weighted index of prices and quantities and use instrumental-variables techniques to estimate the parameters. Based on their static model, they estimate that their food price index was 20 percent higher in 2007 than it would have been in the absence of ethanol production.

We focus our analysis on commodity inventory dynamics, which distinguishes our work from the extant literature. This approach enables us to estimate the price effects of persistent shocks to supply or demand separately from the effects of transitory shocks. This distinction is important in our context because persistent shocks have larger price effects than transitory shocks. The market can respond to a

² See <http://faostat.fao.org/site/609/default.aspx> and the *FAO Statistical Yearbook*.

transitory shock, such as poor growing season weather, by drawing down inventory. This action mitigates the price effect. A persistent shock, such as an increase in current and expected future demand, cannot be mitigated by drawing down inventory.

To identify these two types of shocks, we exploit their differential effects on inventory levels and the term structure of futures prices. For example, all else equal, an increase in this year's consumption demand reduces available inventories and raises spot prices relative to futures prices. This is a transitory shock. In contrast, a predicted increase in next year's consumption demand generates an increase in inventory and an increase in futures prices relative to spot prices. A persistent demand shock is an increase in both this year's demand and next year's expected demand. We develop this framework conceptually in Section 3 and empirically in Section 4. Our method is readily applicable to other problems relating to storable commodities in which the distinction between transitory and persistent shocks matters. Examples may include the effects of climate change, financial speculation, and technological change.

In our application, we use our approach to exploit the fact that informed market participants were well aware by late 2006 of the impending boom in ethanol production. When prices are affected one year by an increase in expected future demand, this effect flows through inventory. We estimate these dynamic effects. Moreover, 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 actual jump in ethanol production.

We estimate the supply and demand for inventory using a partially identified structural vector autoregression (SVAR) model. This approach enables us to trace the dynamic effects of ethanol expansion without imposing strong identifying assumptions. 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 2008 and 2009, when ethanol production increased dramatically. We estimate that average prices over the period from 2006 to 2012 were 34 percent greater in log terms³ than they would have been if US ethanol production had stayed constant at the 2005 level. This estimate comes with a 90 percent confidence interval of 15 to 57 percent. We also estimate that the long-run effect of the mandate is a price increase of 29 percent, with a 90 percent confidence interval ranging from 6 to 78 percent.

2. Background

Ethanol became a significant motor-fuel ingredient in the United States only recently, but 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.⁴ 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.⁵ However, ethanol 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

³ When reporting our results, we use the word *percent* to refer to log differences.

⁴ 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.

⁵ The Farm Chemurgic Movement was the most prominent agricultural advocate of the use of ethanol as a fuel. 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.

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.⁶

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.⁷ 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 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.

⁶ “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.

⁷ 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).

Although ethanol received some favorable treatment in the final legislation,⁸ 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, 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 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 2006.⁹ 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).

⁸ Ethanol was allowed a 1 lb. waiver in the Reid Vapor Pressure (RVP) requirement.

⁹ 20/20 Biofuels Challenge Act of 2005 (S.1609), BOLD Energy Act of 2006 (S.2571.IS, H.R.5331.IH).

Not surprisingly, a massive expansion in ethanol production capacity took place between the 2005 and the 2007 Energy Acts.¹⁰ 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-year projections of the agricultural economy, recognized the expanding RFS and the associated construction boom in its 2007 projections. 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).¹¹ 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.¹² 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

¹⁰ In the remainder of this article, we use the word *ethanol* to refer to ethanol made from corn. Only trivial amounts of other feedstock (e.g., sorghum, barley) have been used commercially in the United States to produce ethanol for motor fuel.

¹¹ Available at <http://usda01.library.cornell.edu/usda/ers/94005/>.

¹² Omnibus Reconciliation Act of 1980 and Energy Security Act of 1980.

with little opposition from ethanol producers' groups such as the National Corn Growers Association and the Renewable Fuels Association.¹³ This lack of opposition suggests that the RFS has high value 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).

The RFS is often justified on environmental grounds, but the greenhouse gas effects of corn-ethanol production are subject to debate. 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, 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). Finally, 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, although such effects would likely be small (de Gorter and Just 2010; Khanna, Ando, and Taheripour 2008).

3. Conceptual Framework

Our core framework is similar to that in Peck (1985, pp. 56-57). It consists of a two-period model of a grain commodity that incorporates three integrated 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 "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 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.

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.

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

$$S_1 - D_1 = -\alpha_0 + \alpha_1 P_1 + \eta_1^S - \eta_1^D \quad (2)$$

$$S_2 - D_2 = \beta_0 - \alpha_0 + \beta_1 E_1[P_2] + \alpha_1 P_2 + \eta_2^S - \eta_2^D. \quad (3)$$

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.

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. This market clears when inventory equals current-period net supply and period 2 net demand, i.e., $I_1 \equiv S_1 - D_1 = D_2 - S_2$.

The price of storage equals the difference between the expected period 2 selling price and the period 1 price, i.e., $E_1[P_2] - P_1$. Following a long literature that originates 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

$$E_1[P_2] - P_1 = \gamma_0 + \gamma_1 \ln(I_1) + \eta_1^{SS} \quad \text{supply of storage.} \quad (4)$$

This specification imposes the constraint that inventory carryover cannot be negative, which implies $I_1 \geq 0$. The marginal cost of storage can, however, be negative. A negative marginal cost of storage can

¹⁴ US corn imports are essentially zero.

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 a 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 in the future (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 inventory 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) and taking expectations over period 2 net demand, we have

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

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

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

$$E_1[P_2] - P_1 = (\alpha_0 - \beta_0 - I_1 - E_1[\eta_2^S - \eta_2^D]) / (\beta_1 + \alpha_1) - (\alpha_0 + I_1 - \eta_1^S + \eta_1^D) / \alpha_1. \quad (5)$$

The demand for storage slopes downward because the market is willing 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 shifted left, this equilibrium could result in a negative price of storage (i.e., futures-market backwardation).

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 helps us identify the effects of ethanol, because we do not need to separately identify the elasticities of demand and supply for current use.

In the case of corn 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 expected future demand curve for corn in Panel B shifted to the right, which implies that the demand-

for-inventory curve shifted to the right in 2006. However, current-year supply and demand remained constant. Thus, the spot price, inventory level, and price of storage all increased.

By 2008, the increase in demand for corn from ethanol plants had become permanent. Figure 3 shows this scenario. Both current and expected future demand have shifted to the right (Panels A and B), which in turn shifted the supply-of-inventory curve in Panel C to the left and the inventory-demand curve in Panel C to the right. 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.

[FIGURE 3 HERE]

Figure 3 illustrates the advantages of our inventory-focused approach in distinguishing transitory from persistent price shocks. Poor growing-season weather is one example of a transitory price shock. Such a shock would shift the supply-of-inventory curve to the left but it would not shift the demand-for-inventory curve, so it would have a smaller price effect than a persistent shock that shifts both curves.

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, even small shocks can have

large price effects because they cannot be mitigated by drawing down inventory. We separate the demand for inventory from the demand for current use for three reasons. First, this approach allows us to separately identify persistent and transitory shocks. Second, it enriches the theory by making predictions not just about the effects of ethanol production on corn prices, but also about the effects on the price of storage. Third, the kink in the total demand curve at low inventory levels means that linear empirical 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, we use a two-period model to show how demand from ethanol producers for corn affects the supply and demand for inventory, the price of storage, and the price of corn. We use a two-period model because it is the simplest setting in which to illustrate these effects. In reality, of course, 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 autoregression model of the supply-of-inventory, demand-for-inventory, and supply-of-storage functions given in equations (2)-(4). 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 2012. 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

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.

(2009) in controlling for aggregate commodity demand. After we describe our data, we present our identification strategy in Section 4.2, our counterfactual experiment in Section 4.3, and our method for estimating long-run effects in Section 4.4.

4.1 Data

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 planting and 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 crop year we take the average daily price in March on the futures contract that reaches 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 $f_t = \ln(F_{t,T} / CPI_t)$, 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,

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

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 average daily Central Illinois cash bids in March 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.¹⁶ Our results also 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 and measure them using

$$r_{t,T} = 0.75g_t, \quad (7)$$

where g_t denotes the yield on one-year Treasury notes plus 200 basis points, and the 0.75 factor reflects the fact that we are calculating the cost of storage over a nine-month horizon. The one-year Treasury is consistent with a nine-month storage period. We add 200 basis points based on the Chicago Mercantile Exchange's method for determining the price of storage in wheat-futures markets. 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).

¹⁶ Garcia, Irwin, and Smith (2012) show that the specific futures-market delivery mechanism sometimes causes the futures price to exceed the expected future spot price. They show that these discrepancies have recently been large for wheat, but over a nine-month storage window, they are small for corn.

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:

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

where CPI is indexed to equal 1 in 1982–83. The additive warehouse cost component reflects the fact that warehousing costs are not proportional to the price of the commodity. Nonetheless, our estimates of the effect of ethanol expansion on futures prices are robust to our assumption that warehousing storage costs equal \$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 it is important to include an additive component to the price of storage.

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 include both government- and privately-held inventory. The US 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. 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.¹⁷ 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 (Carter, Rausser and Smith, 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

¹⁷ Notwithstanding these reasons, our estimates of the price effect are only few percentage points different if we use world inventory excluding China. We exclude China because it often reports large changes in inventory holdings, but it does not tend to manage that inventory in accordance with market signals (Wright (2011)).

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 2009.¹⁸ As a result of this dietary shift, the demand for grain for animal feed increases, which in turn increases corn prices. Additional factors may contribute to the link between global economic activity and corn prices. Frankel (1986) and Rausser et al (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). We use the March value of the index to match the timing of our price data.

Figure 4 presents the resulting index of real economic activity (after removing a linear trend) along with the de-trended time-series 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

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

¹⁸Food and Agriculture Organization, available at <http://faostat3.fao.org>.

where

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

The second equation represents inventory supply, the third represents inventory demand, and the fourth represents supply of storage.¹⁹ In the notation of Section 3, these equations are

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

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

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

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

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

The parameter α_{23} is the short-run (i.e., one-year) elasticity of inventory supply. As shown in Figure 2, 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 elasticities are not identified, because inventory is endogenous in the inventory-demand and supply-of-storage equations.

¹⁹ Our empirical results are robust to additional lags. The AIC and BIC select a single lag.

Most of the year-to-year variation in inventory comes from 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 use 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 (2013) 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.

We make an identifying assumption that there is no feedback from the corn market to global economic activity within one year. This assumption implies zero restrictions in the first row of the matrix A . Total world trade in corn is a small fraction of seaborne trade in dry cargo, the price of which underlies our real economic activity measure. Most dry cargo is industrial commodities such as coal and iron ore. In the decade of the 2000s, total corn trade was less than 2 percent of seaborne dry-cargo trade by weight. During our sample period, world corn trade never exceeded 4.3 percent of seaborne dry-cargo trade.²⁰ Thus, the effect of corn-specific price shocks on real economic activity is likely negligible. Based on our theoretical framework, we also assume that convenience yield shocks do not shift the inventory-demand curve. These zero restrictions leave a single unidentified parameter, so we place bounds only on α_{23} .

²⁰ Corn trade data from the USDA (<http://www.fas.usda.gov/psdonline>), and dry cargo trade data from UNCTAD Stat (<http://unctadstat.unctad.org/ReportFolders/reportFolders.aspx>).

Using estimates from the literature and with some introspection, we could exactly identify our model by choosing a specific numerical value for the short-run supply elasticity. This was the approach used by Blanchard and Perotti (2002) 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. In our case, we could use the estimates of Adjemian and Smith (2012), who use the price response to USDA crop forecasts during the period from 1980 to 2011 to estimate the demand flexibility (inverse elasticity) for corn. We show in Appendix A that their estimates imply $\alpha_{23} \approx 4.4 - 1 / (\alpha_{32}(1 + \alpha_{43}) + \alpha_{42})$.

Rather than imposing specific values, we impose bounds on α_{23} . Here, we introduce three assumptions that imply bounds on the parameters that can be used to partially identify our model. The elasticity of inventory supply is

$$\alpha_{23} = \eta^s \frac{Q^s}{I} - \eta^u \frac{Q^u}{I},$$

where η^s and η^u denotes the production (supply) and current-use (demand) elasticities, I/Q^s is the ratio of inventory to production, and I/Q^u is the ratio of inventory to use. The inventory to use ratio 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. The supply elasticity is non-negative and likely close to zero because planted acreage and inventory carryover are essentially determined by March of each year. Thus, we place a lower bound of $0 - -0.1/0.4 = 0.25$ 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 $0.25 \leq \alpha_{23} \leq 1/\alpha_{32}$.

In sum, we base these bounds on 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.

Proceeding under these assumptions, we estimate the model parameters using data from 1961 to 2005. Based upon the estimated parameters, we take two approaches to estimating the effects of the RFS in corn prices. First, we forecast prices and inventory for the period from 2006 to 2012 and conduct a counterfactual experiment to assess the dynamic impact of expanding ethanol production. Second, we deduce implied effects from our parameter estimates through parallel shifts of the inventory supply and demand curves as in Figure 3. Next, we describe these two methods.

4.3. Estimating the Ethanol Effect Using 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 2006–12 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 in 2006-12 emanated 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 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 2006–12. This experiment produces an estimate of the effect of ethanol production on corn prices under the assumption of no other inventory demand or supply shocks in the 2006–12 period.

The first six years of our counterfactual period produced no extreme Corn Belt weather events, but corn production did fluctuate significantly during this period. Then, in 2012 this region experienced its worst drought for 50 years. 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. In 2012, production came in 27 percent below expectations. To incorporate these surprises in our counterfactual scenario, we generate

$$\begin{bmatrix} REA_t^{CF} \\ i_t^{CF} \\ f_t^{CF} \\ cy_t^{CF} \end{bmatrix} = \hat{A}^{-1} \hat{B} \begin{bmatrix} REA_{t-1}^{CF} \\ i_{t-1}^{CF} \\ f_{t-1}^{CF} \\ cy_{t-1}^{CF} \end{bmatrix} + \hat{A}^{-1} \hat{\Gamma} Z_t + \hat{A}^{-1} \begin{bmatrix} \hat{u}_{1t} \\ \delta_t \\ 0 \\ \hat{u}_{4t} \end{bmatrix}, \quad (11)$$

where $\delta_t = S_t / 40$ and S_t denotes the production surprise in year t , which we measure in millions of metric tons. We standardize the shock by the average inventory the last 10 years of our estimation

sample, which was 40 million metric tons. By using this functional form for δ_t , we allow an approximate linear shift of magnitude S_t in the quantity of inventory supplied.

4.4. Estimating the Long-Run Ethanol Effect Directly

We can estimate the long-run effect of the mandate directly from the model parameters. We expect the long-run price effect to be less than the short-run effect as a longer run gives the opportunity for land-use change. The long-run effect would be zero if factors of production had infinitely elastic supply, but we have no reason to expect this to be so. The dominant factor of production for corn is cropland, the expansion of which is limited (Searchinger et al (2008)).

This difference between the 2007 and 2005 mandates is approximately 5.5b gallons of annual ethanol production in the years 2010-2012. We take these 5.5b gallons as the permanent increase in ethanol demand in the 2007 mandate. Ethanol plants produce about 2.8 gallons of ethanol from each bushel of corn, but a third of that bushel is returned to the food system in the form of distiller's grains used for animal feed. Thus, the RFS implies a permanent demand increase of 1.3 billion bushels, or 33.4 million metric tons (mmt). In the long run, the supply of inventory shifts left by this amount and the demand for inventory shifts right by this amount, as illustrated in Figure 3. The short run impacts differ because the mandate was phased in over time and because inventory demand may have moved by more than the long-run amount in the short run to potentially cover multiple years. This shift is approximately the magnitude of trend inventory levels at the end of our sample.

The long-run relationships implied by the VAR model can be depicted by setting all shocks to zero, i.e.,

$$AX_t^{LR} = BX_{t-1}^{LR} + \Gamma Z_t \tag{12}$$

This equation describes the long-run real economic activity, inventory supply, inventory demand, and supply of storage curves. We shift the inventory supply curve to the left by 33.4 mmt and the inventory

demand curve to the right by the same amount. We then solve for new values of inventory, futures price and convenience yield holding real economic activity constant. See Appendix B for details on our solution method.

These parallel shifts are nonmarginal, and their magnitude is approximately equal to the trend level of inventory in the latter part of our sample. This fact makes our results potentially sensitive to our specification of a log linear functional form. To investigate the robustness of our results to functional form, we also estimate the long-run ethanol effect using several linear approximations. Specifically, we estimate the effect on prices of small parallel shifts in the inventory supply and demand curves and extrapolate linearly. For example, we estimate the effect of 3.34 mmt parallel shifts and multiply the result by 10 to approximate the effect of 33.4 mmt shifts.

5. Results

5.1 Parameter Estimates and Impulse Responses

Table 1 contains the reduced-form parameter estimates²¹ 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.

²¹ The reduced-form parameters correspond to $A^{-1}B$ in (9) and are estimated by OLS.

If we fix α_{23} based on the assumption that the difference between the inventory supply and demand elasticities equals $\alpha_{23} = 4.4 - 1 / (\alpha_{32}(1 + \alpha_{43}) + \alpha_{42})$ (as suggested by the discussion in Section 4.2 and Appendix A), then the estimated short-run elasticity of inventory supply equals 1.79. Under this same assumption, the estimated short-run elasticity of inventory demand equals $-1/0.22 = -4.55$. 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 4.03 to 0.25 for α_{23} . 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 $-1/0.18 = -5.56$ to $-1/0.25 = -4.00$. The supply-of-storage parameters are largely unaffected by variation within the identified set.

Figure 5 shows impulse-response functions for one-time one standard deviation structural shocks. The shaded box in the figure signifies the identified set, and the vertical lines above and below indicate confidence intervals with greater than 90 percent coverage.²² 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]

²² 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. We keep only draws that satisfy our identification conditions $\alpha_{23} > 0.25$ and $\alpha_{32} > 0$. 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 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 $\alpha_{23} \approx 4.4 - 1 / (\alpha_{32}(1 + \alpha_{43}) + \alpha_{42})$. 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 2006–12. 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 price increases in 2006–07 and again in 2010–12. Inventory-supply shocks affected prices in several episodes, especially 2010–12. In 2010 and 2011, respectively, actual production was 7 and 8 percent below expectations due to below-average weather during the growing season. Then in 2012, the Midwestern United States experienced a drought that, by some measures, was the worst in at least 50 years. The drought caused corn production to be 27 percent below what was expected at planting time. In our model, this event manifests as a negative inventory-supply shock, which raises prices and lowers inventory.

Convenience yield is driven mostly by inventory supply, which would be expected from a relatively constant supply-of-storage curve that the demand curve slides up and down as inventory levels change. High inventory demand dampens convenience yield in 2006–12, as implied by our theory.

[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 $\alpha_{23} \approx 4.4 - 1 / (\alpha_{32}(1 + \alpha_{43}) + \alpha_{42})$, and Table 2 shows the ranges implied by the identified set. If there had been no inventory demand shocks in 2006–12, 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 64 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 futures 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 3: 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 2006–12 was the growth of the ethanol industry. The red line in Figure 7 shows the counterfactual case of no inventory supply or demand shocks between 2006 and 2012. The green line indicates lower inventory and higher prices than the red line because it includes the actual 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 42 percent greater and futures prices were 41 percent greater than they would have been in the absence of inventory-supply and inventory-demand shocks. But note that this counterfactual price is still 18 percent greater, on average, than the 2005 price. We thus deduce that strong global growth is

responsible for almost half of the average corn-price increase since 2005, and corn supply and demand is responsible for the remainder.

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. A major drought did occur in 2012. 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 prior to 2012 it has little effect on the average difference between the actual and counterfactual values. In summary, based on this counterfactual, we estimate that ethanol production raised corn prices by 34 percent, on average, in 2006-2012. The 90 percent confidence interval for this estimate is [0.17, 0.54].

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 35 and 36 percent for futures prices and between 31 and 36 percent for cash prices. The associated 90 percent confidence intervals are [0.20, 0.59] for futures and [0.15, 0.57] 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 7 to 24 percent across the identified set; this wide range is generated by the range of α_{23} .

To check the robustness of these estimates, we applied our counterfactual analysis to the 1999-2005 crop years. This is a kind of placebo test. Using the counterfactual in (11), which allows for production shocks, we estimate an average counterfactual cash price 7 percent greater than the observed price. This estimate has a 90 percent confidence interval of [-0.20, 0.06] and so it is not statistically significant. Moreover, the confidence interval includes zero not just for the average, but also in all but one of the 7 years.

Our analysis also reveals 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 ethanol-demand increase caused corn prices to rise again significantly above the counterfactual values. In these two years, we estimate that corn prices were 52 and 56 percent greater than they would have been without the ethanol-induced shocks.

In the absence of the ethanol shocks observed since 2006, the 2012 drought would have caused inventory to decline by significantly more than it did. 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 current market environment, 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 relatively low entering 2012 even without ethanol production. Thus, the drought would still have had a substantial price effect; our counterfactual cash price is 28 percent below the actual price. Due to inventory demand, the futures price is affected more than the spot price in 2012.

5.3 Estimated Long-Run Effect

Figure 8 shows the estimated long-run effect on cash prices using four different methods, which vary by the extent of linear extrapolation. As described in Section 4.4, we conduct parallel shifts of $\pi \cdot 33.4$ mmt in the inventory supply and demand curves and multiply the result by $1/\pi$ to approximate the effect of 33.4 mmt shifts. For $\pi=0.1$, the estimated effect is 29 percent, with the identified set covering the range [0.24, 0.29] and a 90 percent confidence interval of [0.06, 0.78]. When we estimate

directly the effect of 33.4 mmt parallel shifts ($\pi=1$), we obtain a cash price effect of 0.25, and when we linearly extrapolate using $\pi=0.1$, we estimate a 0.29 effect. Thus, the point estimates are robust to functional form.

The confidence interval on the cash price effect is robust to various levels of linear extrapolation. We obtain ranges of [0.06, 0.82], [0.06, 0.78], and [0.06, 0.85] for $\pi=0.01$, 0.1, and 0.5, respectively. Only for parallel shifts of the full 33.4 mmt do we obtain a different range; the interval covers [0.05, 1.51] in that case. This confidence interval is sensitive to functional form because 33.4 mmt is approximately equal to trend inventory, which means that a leftward shift of this magnitude in inventory supply can generate an equilibrium a very steep part of the inventory demand curve. Thus, in some bootstrap draws we obtain a large estimated price effect, in essence because we take the log of a number close to zero. Because the extrapolated estimates are naturally bounded away from this region and are robust across values of π , we find them the most credible.

[FIGURE 8 HERE]

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. The rise of 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 facilities exist, jumped in 2006 and has remained high since that time, as shown in Figure 9.

[FIGURE 9 HERE]

Relative production of corn in Iowa and Illinois has changed little over time, and Figure 9 shows no discernible trend in the relative price between 1960 and 2005. Moreover, Figure 9 shows that in the early 2000s, these two states had very similar ethanol-production capacity, namely, 700 million gallons per year.²³ 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 VAR results.

6.2 Financial Speculation

Commodity prices rose and fell dramatically in the latter half of the 2000s (Carter, Rausser, and Smith 2011). In addition to 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 funds take positions only on the long side of the market. If traders on the short side of the market were unable to accommodate the increased demand for long futures positions, then futures prices would rise. 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

²³ The two ethanol-production-capacity curves in Figure 9 represent the sum of operating capacity and capacity under construction.

price of the underlying commodity, then there should be a quantity change in the form of increased inventory (Hamilton 2009).²⁴

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 10 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. These price patterns do not suggest that a broad speculation drove corn-inventory demand to increase in the fall of 2006.

[FIGURE 10 HERE]

6.3. Ethanol Refining Margin

Figure 11 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,²⁵ 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

²⁴ 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).

²⁵ http://www.card.iastate.edu/research/bio/tools/hist_eth_gm.aspx

of the graph, which we label “net returns,” represents the difference between the ethanol price and the sum of the three cost components.

[FIGURE 11 HERE]

Prior to the fall of 2006, ethanol prices far exceeded the three cost components during three periods: 2000–01, 2004, and 2005–06. Ethanol prices spiked during Hurricane Katrina, in August 2005, and then reached an even higher peak in mid-2006. This 2006 spike was caused by a supply crunch generated by the legislated 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 (2012) 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. This approach enables us to separately identify persistent and transitory shocks to corn prices.

We isolate two 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 34 percent lower from 2006 through 2012 if the ethanol mandate had not been expanded in 2007.

The ethanol mandate is controversial and continues to face economic and political challenges. During the 2012 drought, several state governors and other groups including livestock producers requested a temporary waiver of the RFS mandate. The EPA has the authority to temporarily waive the mandate if it is causing “severe economic or environmental harm to a region or the nation”. However, the temporary-waiver request was denied. In 2013, the mandate is contending with the so-called blend-wall constraint, namely that the mandate demands greater ethanol content than the 10 percent that has been approved by EPA for blending with conventional fuel. Alternative fuel blends that use 15 and 85 percent ethanol have been approved for certain vehicles, but these have had little success in the market. Another way to meet the mandate in the presence of the blend wall is to massively expand biodiesel production from soybeans, which would have potentially large effects on another food commodity. Thus, the methods and results in this paper are of continuing policy relevance.

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Table 1: VAR Parameter Estimates

Equation	REA	Inventory	Futures	Conv. Yield
<i>Reduced Form Estimates: A⁻¹B</i>				
<i>REA</i> _{t-1}	0.626* (0.133)	-0.692 (0.409)	0.233 (0.140)	0.022 (0.061)
<i>Inventory</i> _{t-1}	-0.060 (0.055)	0.643* (0.180)	0.003 (0.053)	0.019 (0.029)
<i>Futures</i> _{t-1}	-0.279* (0.141)	0.817 (0.439)	0.604* (0.120)	-0.047 (0.064)
<i>Conv. Yield</i> _{t-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)
<i>A Matrix: imposing $\alpha_{23} = 4.4 - 1 / (\alpha_{32}(1 + \alpha_{43}) + \alpha_{42})$</i>				
<i>REA</i>	1	0	0	0
<i>Inventory Supply</i>	0.86	1	-1.79	-1.79
<i>Inventory Demand</i>	-0.41	0.22	1	0
<i>Supply of Storage</i>	0.06	0.14	0.14	1
<i>A Matrix: Identified Set</i>				
<i>REA</i>	1	0	0	0
<i>Inventory Supply</i>	[0.31,1.67]	1	[-4.03, -0.25]	[-4.03, -0.25]
<i>Inventory Demand</i>	[-0.42,-0.40]	[0.18,0.25]	1	0
<i>Supply of Storage</i>	[0.06,0.07]	[0.13,0.14]	[0.12,0.15]	1
<i>A Matrix: >90% Confidence Interval</i>				
<i>REA</i>	1	0	0	0
<i>Inventory Supply</i>	[-0.12,2.47]	1	[-4.98, -0.25]	[-4.98, -0.25]
<i>Inventory Demand</i>	[-0.51,-0.28]	[0.13,0.29]	1	0
<i>Supply of Storage</i>	[-0.02,0.14]	[0.11,0.17]	[0.05,0.25]	1

Notes: Sample range: 1961–2005; standard errors in parentheses; * indicates significance at 5%; model selection criteria values are AIC_c=-687.72 and BIC=-667.40; for the two-lag model, we obtain AIC_c = -670.02 and BIC = -639.77, so the one-lag model is favored. We obtain the confidence intervals using a recursive-design wild bootstrap (see footnote 22).

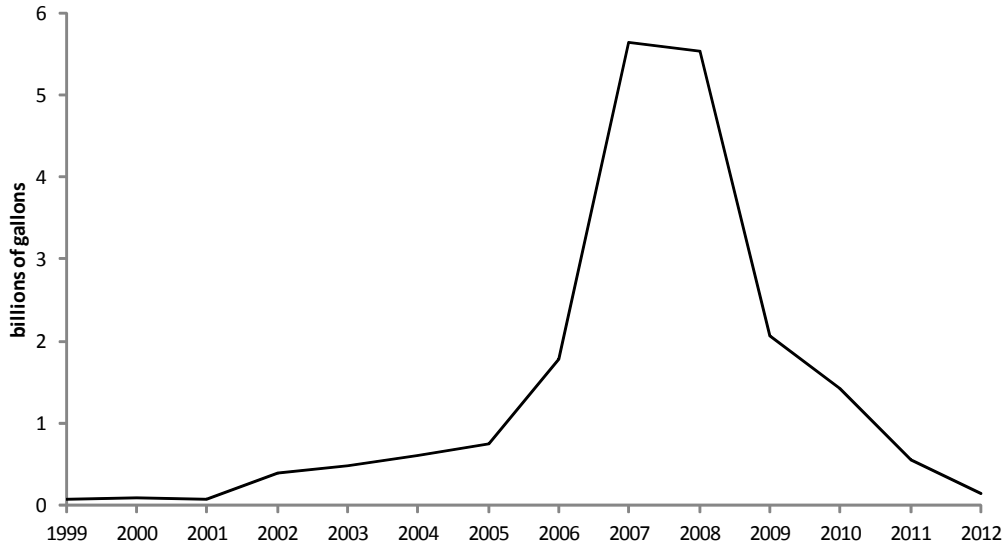
Table 2: Log Difference between Actual and Counterfactual

	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	Average
<i>No Inventory-Demand Shocks</i>								
Inventory	0.25	0.54	0.47	0.46	0.93	0.97	0.97	0.64
Fut. Price	0.20	0.35	0.11	0.00	0.26	0.17	0.17	0.20
Conv. Yield	-0.06	-0.09	-0.01	0.01	-0.06	-0.03	-0.03	-0.05
Cash Price	0.14	0.25	0.10	0.01	0.21	0.14	0.14	0.15
<i>No Inventory-Demand or -Supply Shocks</i>								
Inventory	-0.12	0.31	0.46	0.42	-0.18	-0.63	-1.17	-0.13
Fut. Price	0.28	0.41	0.14	0.02	0.58	0.66	0.75	0.41
Conv. Yield	-0.02	-0.08	-0.02	0.01	0.00	0.07	0.12	0.01
Cash Price	0.26	0.33	0.12	0.03	0.58	0.73	0.88	0.42
<i>No Inventory-Demand Shocks; Inventory-Supply Shocks from Production Surprises Only</i>								
Inventory	-0.12	0.08	0.39	0.00	0.05	-0.07	0.66	0.14
Fut. Price	0.28	0.46	0.16	0.13	0.56	0.55	0.33	0.35
Conv. Yield	-0.02	-0.05	-0.02	0.05	-0.04	0.01	-0.05	-0.02
Cash Price	0.26	0.41	0.14	0.18	0.52	0.56	0.28	0.34
<i>Identified Set; No Inventory-Demand Shocks; Inventory-Supply Shocks from Production Surprises Only</i>								
Inventory	[-0.12,-0.10]	[-0.04,0.18]	[0.26,0.48]	[-0.31,0.20]	[-0.01,0.14]	[-0.24,0.16]	[0.01,1.59]	[0.07,0.24]
Fut. Price	[0.28,0.28]	[0.45,0.47]	[0.14,0.19]	[0.08,0.17]	[0.56,0.56]	[0.53,0.57]	[0.24,0.45]	[0.35,0.36]
Conv. Yield	[-0.03,-0.02]	[-0.06,-0.05]	[-0.02,-0.01]	[0.03,0.07]	[-0.08,-0.01]	[-0.03,0.04]	[-0.15,0.03]	[-0.04,0.00]
Cash Price	[0.25,0.27]	[0.39,0.43]	[0.12,0.17]	[0.11,0.24]	[0.48,0.55]	[0.50,0.62]	[0.09,0.48]	[0.31,0.36]
<i>>90% Confidence Interval on Identified Set; No Inventory-Demand Shocks; Inventory-Supply Shocks from Production Surprises Only</i>								
Inventory	[-0.36,0.27]	[-0.42,0.63]	[-0.24,0.97]	[-0.82,0.56]	[-0.64,0.62]	[-0.74,0.56]	[-0.49,2.02]	[-0.35,0.60]
Fut. Price	[0.18,0.35]	[0.29,0.63]	[-0.05,0.43]	[-0.10,0.44]	[0.34,0.87]	[0.36,0.87]	[0.09,0.73]	[0.20,0.59]
Conv. Yield	[-0.08,0.02]	[-0.11,0.00]	[-0.09,0.04]	[-0.03,0.12]	[-0.15,0.05]	[-0.08,0.09]	[-0.19,0.07]	[-0.09,0.04]
Cash Price	[0.12,0.35]	[0.22,0.59]	[-0.09,0.41]	[-0.09,0.50]	[0.25,0.86]	[0.33,0.90]	[-0.06,0.75]	[0.15,0.57]
<i>Production Surprises (MMT)</i>								
Actual Prod.	267.50	331.18	307.14	332.55	316.17	313.92	273.83	
May Forecast	267.98	316.50	307.99	307.10	339.61	343.04	375.68	
Surprise	-0.48	14.68	0.85	25.45	-23.45	-29.12	-101.85	

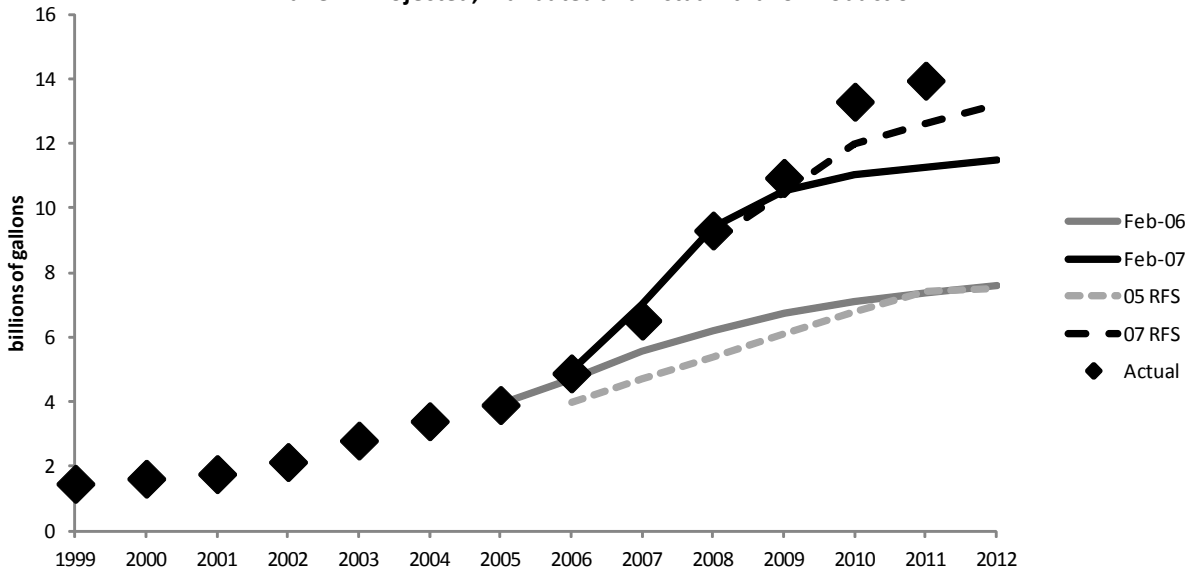
Notes: Here we define the log cash price as $f_t + cy_t$. The entries in this table are results from the counterfactual experiment described in Section 4.3.

Figure 1: Growth of the Ethanol Industry

Panel A: Capacity Under Construction or Expansion (beginning of year)



Panel B: Projected, Mandated and Actual Ethanol Production



Notes: The solid lines in Panel B, show USDA projections, the dashed lines show the mandated quantities under the RFS, and the diamonds show actual ethanol production. Data sources are USDA baseline projections, Renewable Fuels Association Annual Industry Outlook, and the Energy Information Administration of the US Department of Energy.

Figure 2: Two-Period Commodity-Market Equilibrium

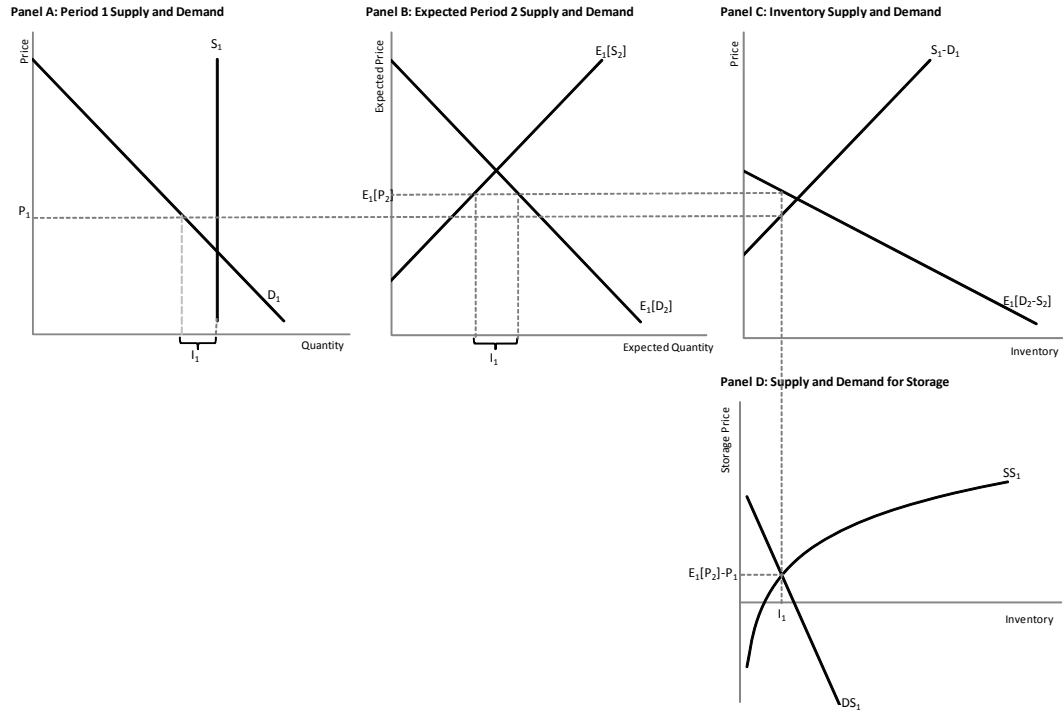


Figure 3: A Permanent Increase in Demand

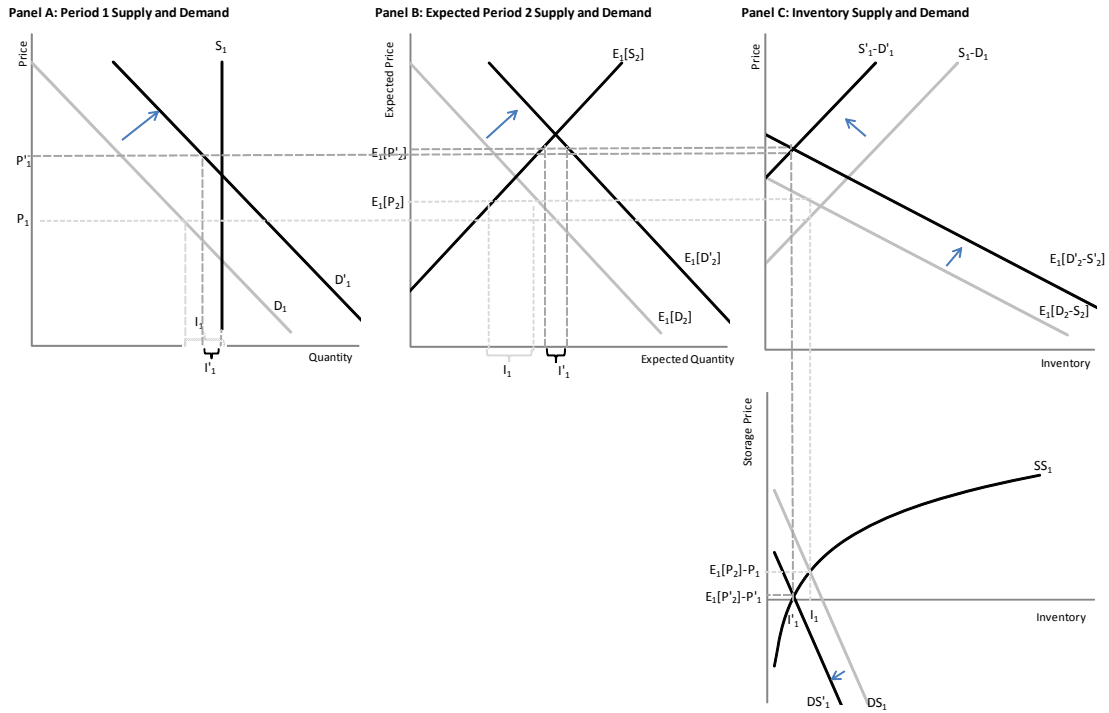
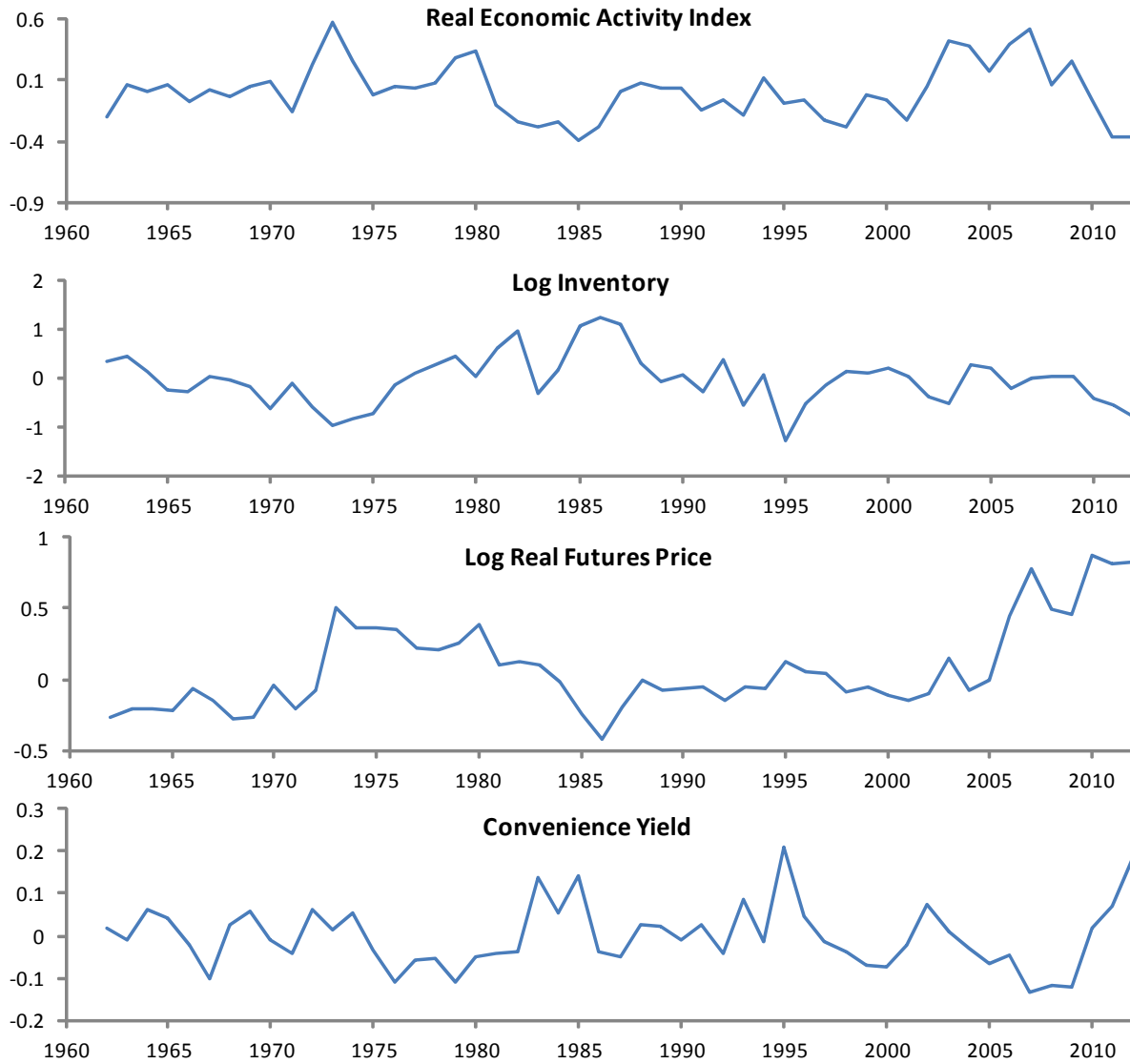
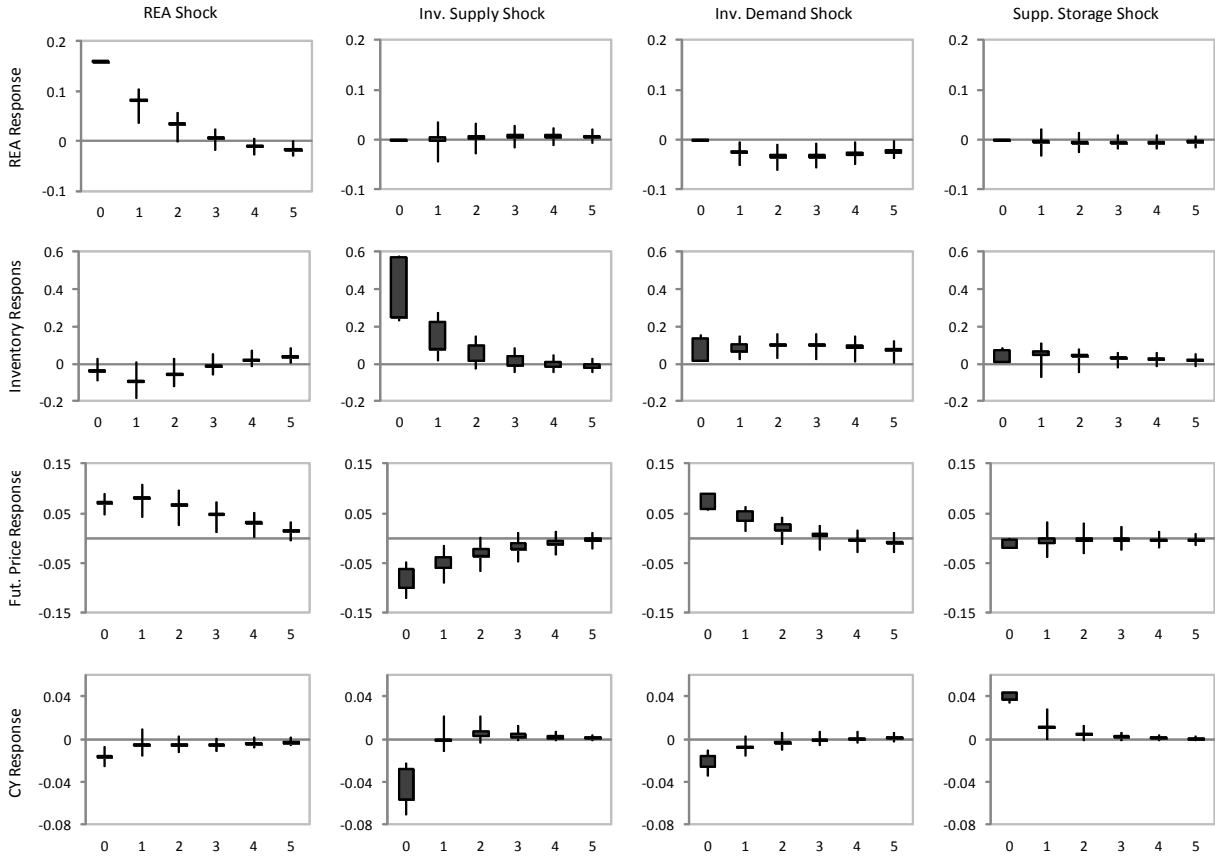


Figure 4: De-Trended Data for Key Variables



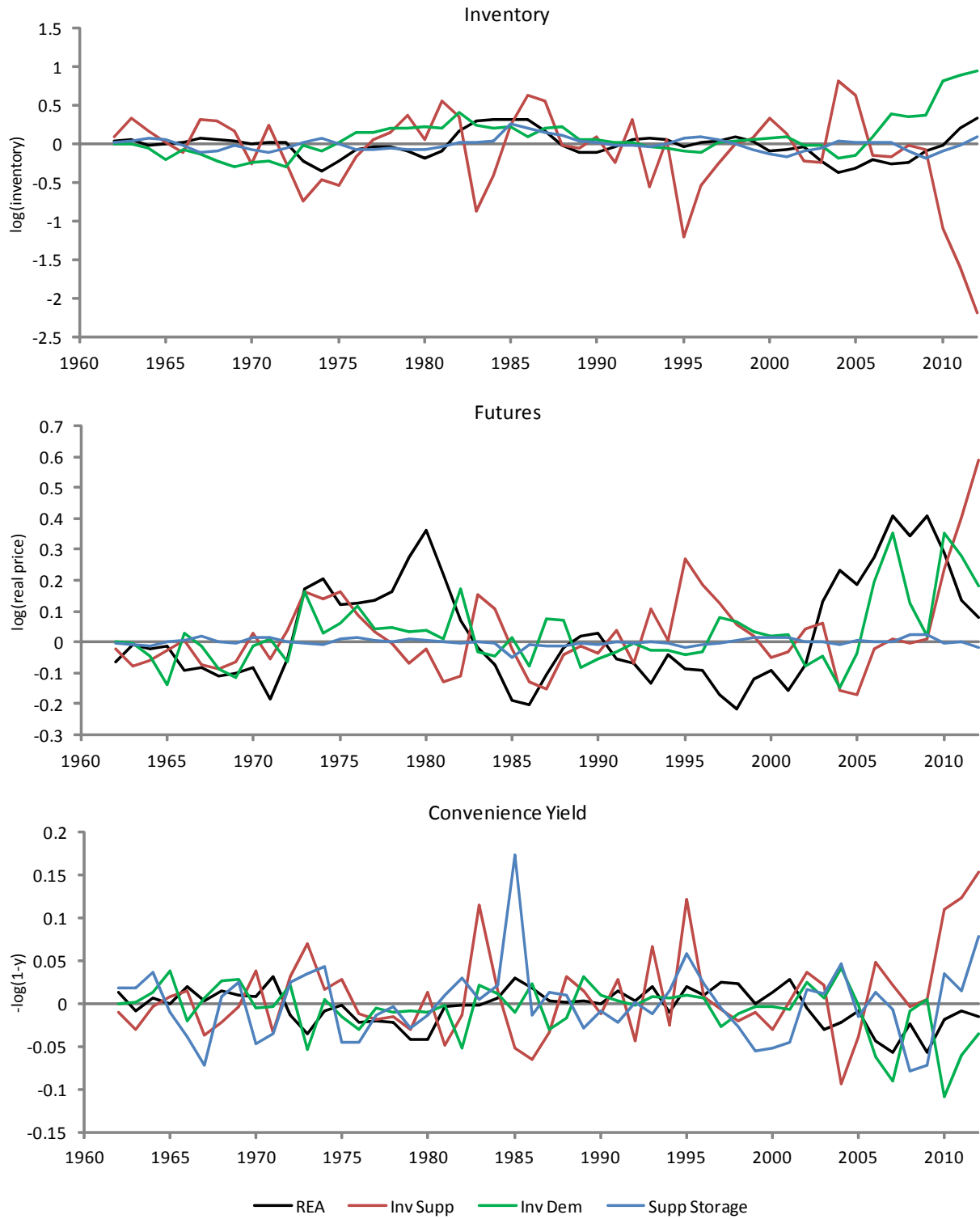
Notes: For clarity, this figure shows linearly de-trended series, where we estimate the trend in the pre-ethanol period (1962-2005). For the VAR estimation, we use the actual series and include a constant and linear trend in each equation of the model.

Figure 5: Impulse Responses



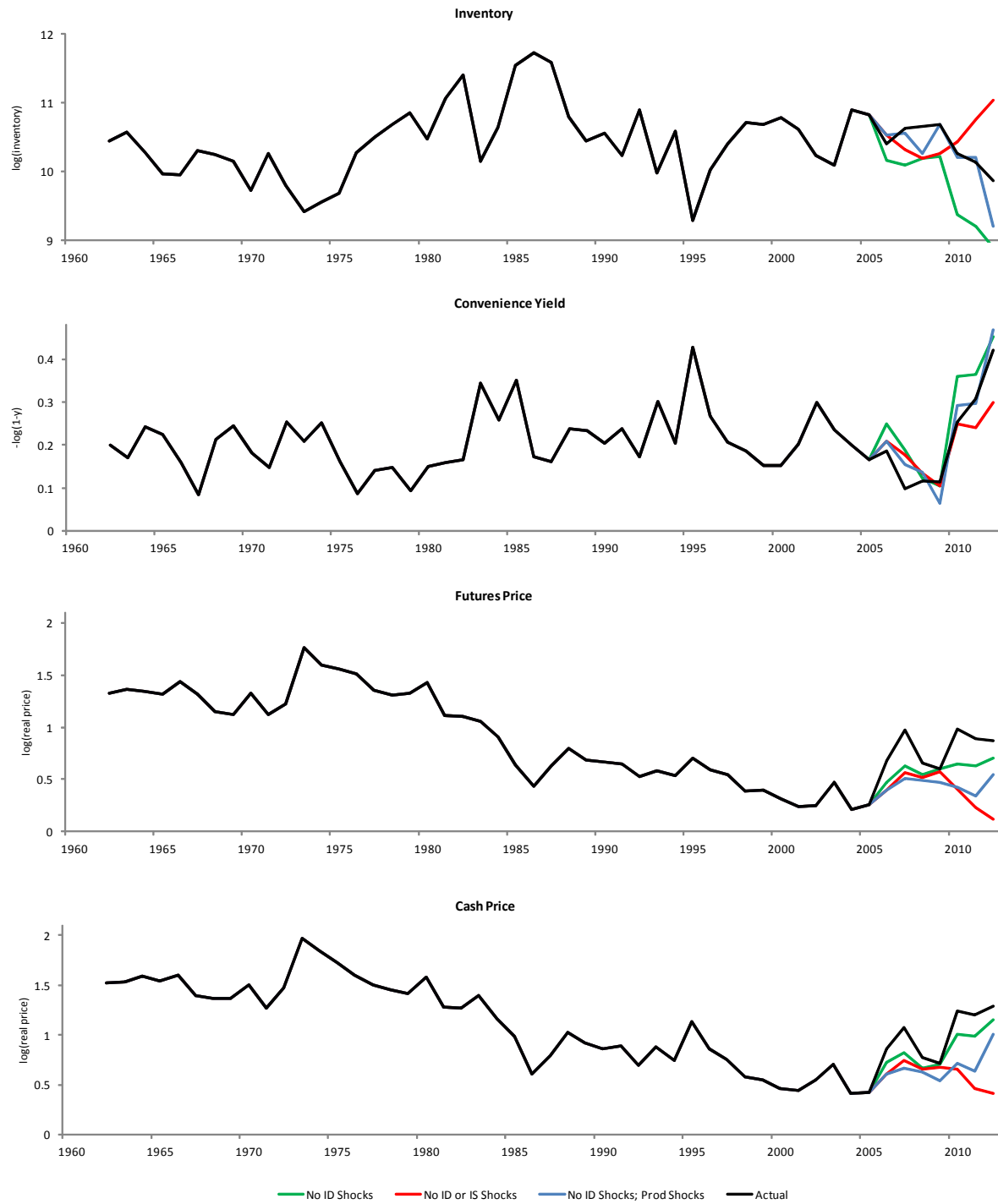
Notes: Responses to one-time one-standard-deviation shocks. The dark boxes indicate the range of impulse responses in the identified set. The vertical bars indicate estimated confidence intervals that cover the true parameter with probability greater than 0.90. We obtain these intervals using a recursive-design wild bootstrap (see footnote 22).

Figure 6: Historical Decomposition



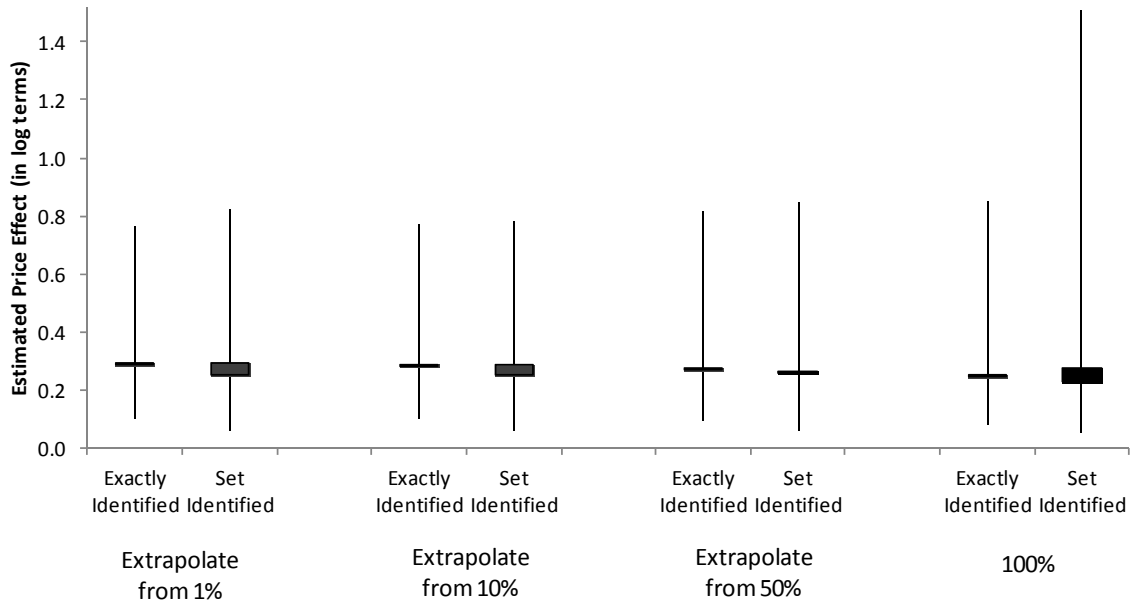
Notes: Figures show contributions of each shock to the relevant series. The sum of the contributions equals the observed data (net of trend).

Figure 7: Counterfactual Analysis



Notes: Here we define the log cash price as $f_t + cy_t$. The various lines are generated from the counterfactual experiment described in Section 4.3.

Figure 8: Long-Run Cash-Price Effect of Ethanol Mandate



Notes: We conduct parallel shifts of the estimated inventory supply and demand by the amounts of $\pi \cdot 33.4$ for $\pi=0.01, 0.1, 0.5,$ and 1 . We multiply the resulting price change by $1/\pi$ to estimate the effect of 33.4mmt shifts. The dark boxes indicate the range of estimated price effects 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 22).

Figure 9: Relative December Corn Prices in Iowa and Illinois

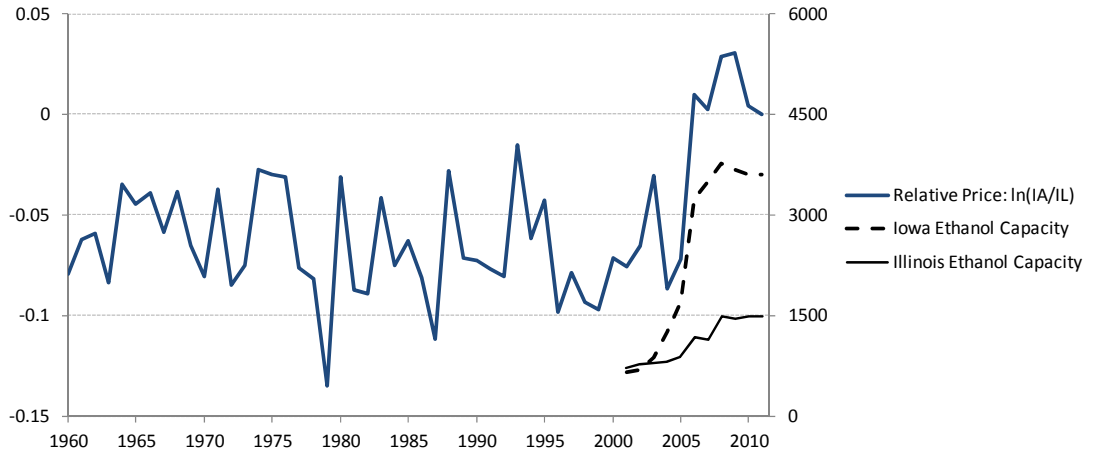


Figure 10: Real Prices of Four Major Commodities (Indexed to 100 in 2000)

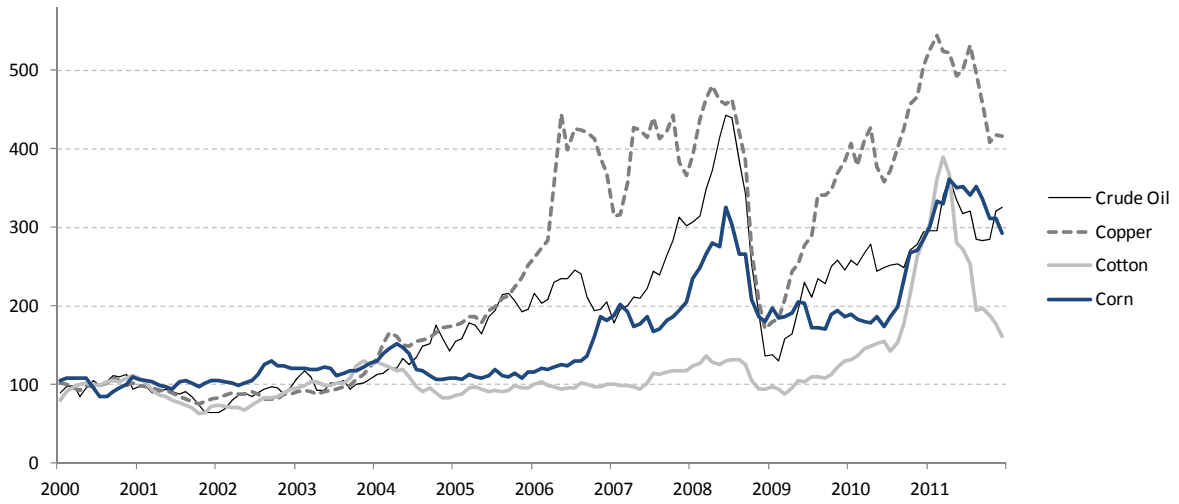
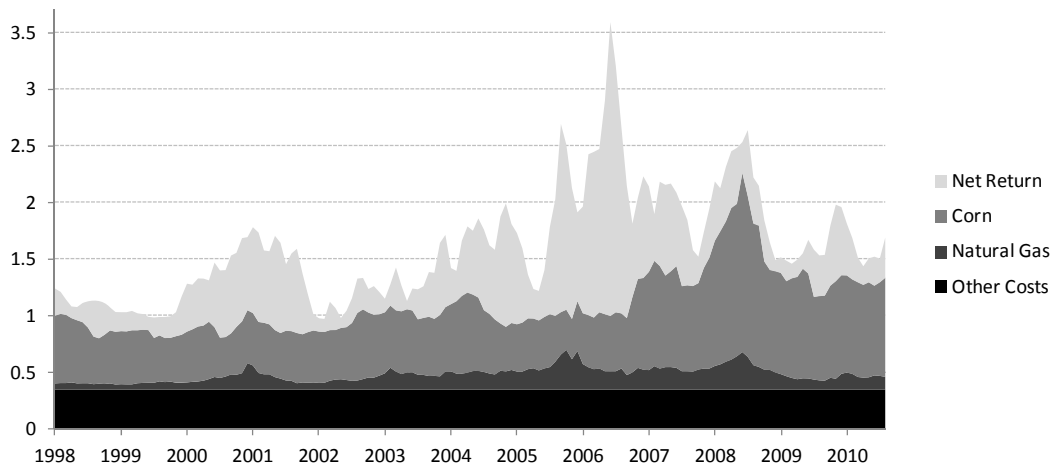


Figure 11: Ethanol Price Decomposed Into Cost Components



APPENDIX

Appendix A: Conditions for Exact Identification

Here, we derive a restriction on the parameters that exactly identifies our model. 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

$$\theta^s \equiv \frac{dI^s}{dP} \frac{P}{I} = \frac{dQ^s}{dP} \frac{P}{I} - \frac{dQ^u}{dP} \frac{P}{I} = \left(\eta^s - \eta^u \frac{Q^u}{Q^s} \right) \frac{Q^s}{I}, \quad (\text{A1})$$

where we define the production (supply) and current-use (demand) elasticities, respectively, as

$$\eta^s \equiv \frac{dQ^s}{dP} \frac{P}{Q^s} \text{ and } \eta^u \equiv \frac{dQ^u}{dP} \frac{P}{Q^u}. \text{ Note also that total demand equals demand for current use plus}$$

inventory demand (i.e., $Q^d = Q^u + I^d$). Thus, elasticity of total demand is

$$\eta^d \equiv \frac{dQ^d}{dP} \frac{P}{Q^d} = \frac{dQ^u}{dP} \frac{P}{Q^d} + \frac{dI^d}{dP} \frac{P}{Q^d} = \eta^u \frac{Q^u}{Q^d} + \theta^d \frac{I}{Q^d}, \quad (\text{A2})$$

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

$$\theta^s = \left(\eta^s - \eta^d + \theta^d \frac{I}{Q} \right) \frac{Q}{I}, \quad (\text{A3})$$

which can be rewritten as

$$\theta^s - \theta^d = \left(\eta^s - \eta^d \right) \frac{Q}{I}. \quad (\text{A3a})$$

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 (A3a). 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 inventories as a proportion of use equal 0.18. Thus, at average inventory levels, we expect from (A3a) 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 (A1)–(A3) imply $\theta^s \equiv \alpha_{23}$. Similarly, combining the inventory-demand and supply-of-storage equations (9b and 9c) implies

$$\frac{1}{\theta^d} \equiv \frac{d(f + cy)}{di} = -\alpha_{32}(1 + \alpha_{43}) - \alpha_{42}, \quad (\text{A4})$$

which implies

$$\theta^d = -1 / (\alpha_{32}(1 + \alpha_{43}) + \alpha_{42}). \quad (\text{A5})$$

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

To fully identify our model, we could impose the restriction $\alpha_{23} + 1 / (\alpha_{32}(1 + \alpha_{43}) + \alpha_{42}) = 4.4$.

Appendix B: Solving for Effect of Parallel Shifts in the Inventory Supply and Demand Curves

The long-run relationships implied by the VAR model can be depicted by setting all shocks to zero, i.e.,

$$AX_t^{LR} = BX_{t-1}^{LR} + \Gamma Z_t \quad (\text{A6})$$

where

$$X_t^{LR} = \begin{bmatrix} REA_t^{LR} \\ \log(I_t^{LR}) \\ f_t^{LR} \\ cy_t^{LR} \end{bmatrix} \quad \text{and} \quad Z_t' = [1 \quad t]$$

We write

$$A = \begin{bmatrix} A'_1 \\ A'_2 \\ A'_3 \\ A'_4 \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} B'_1 \\ B'_2 \\ B'_3 \\ B'_4 \end{bmatrix}.$$

The second equation is the inventory-supply equation, which we shift to the left by amount δ , and the third equation is the inventory-demand equation, which we shift to the right by amount δ . We hold REA fixed at the long-run values in (A6) and solve for the other three variables in 2011 and 2012. We also impose that these shifts change the level of the variables but not the long-run trends.

Thus, we solve the following three equations for $f_t^*, l_t^*, cy_t^*, f_{t-1}^*, l_{t-1}^*$, and cy_{t-1}^* in $t=2012$

$$\begin{aligned} A'_2 \begin{bmatrix} REA_t^{LR} \\ \log(l_t^* + \delta) \\ f_t^* \\ cy_t^* \end{bmatrix} &= B'_2 \begin{bmatrix} REA_{t-1}^{LR} \\ \log(l_{t-1}^* + \delta) \\ f_{t-1}^* \\ cy_{t-1}^* \end{bmatrix} + \Gamma'_2 Z_t \\ A'_3 \begin{bmatrix} REA_t^{LR} \\ \log(l_t^* - \delta) \\ f_t^* \\ cy_t^* \end{bmatrix} &= B'_3 \begin{bmatrix} REA_{t-1}^{LR} \\ \log(l_{t-1}^* - \delta) \\ f_{t-1}^* \\ cy_{t-1}^* \end{bmatrix} + \Gamma'_3 Z_t \\ A'_4 \begin{bmatrix} REA_t^{LR} \\ \log(l_t^*) \\ f_t^* \\ cy_t^* \end{bmatrix} &= B'_4 \begin{bmatrix} REA_{t-1}^{LR} \\ \log(l_{t-1}^*) \\ f_{t-1}^* \\ cy_{t-1}^* \end{bmatrix} + \Gamma'_4 Z_t \end{aligned}$$

subject to $X_t^* - X_{t-1}^* = X_t^{LR} - X_{t-1}^{LR}$, where

$$X_t^* = \begin{bmatrix} REA_t^{LR} \\ \log(l_t^*) \\ f_t^* \\ cy_t^* \end{bmatrix}.$$