Effects of the Renewable Fuel Standard on Corn, Soybean and Wheat Prices

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Summary

The Renewable Fuel Standard (RFS2) became law in 2007. It dictates the minimum volume of biofuels such as ethanol and biodiesel that must be used each year for transportation fuel. In a recently published study, Carter, Rausser and Smith (2017) use a new econometric model to estimate the effects of the RFS on the corn market. They estimate that the RFS2 raised corn prices by about 30. This report summarizes their study and extends it to the soybean and wheat markets. I find that the RFS2 increased soybean and wheat prices by about 20%.

RFS2 Background

Ethanol has a long history as a prospective motor fuel.[2] In the 1920s, oilfields in the eastern US were in decline and agricultural prices were low as European agricultural production recovered from World War I. Lower agricultural prices motivated US farmers to look to ethanol as an alternative source of demand for their crops. During the Great Depression, the Farm Chemurgic Movement worked closely with the US Department of Agriculture (USDA) on a farm-relief program that would subsidize ethanol production from farm crops.

However, large new oil fields were soon discovered in the west, which led to high oil production and low prices. Ethanol was not price competitive and faded into the background until the oil shocks of the 1970s. Beginning in 1978, variants of the RFS entered Congress on a regular basis, but it was not until the 1990 amendments to the Clean Air Act that ethanol gained a foothold. These amendments required that oxygenate additives be blended into gasoline in regions prone to poor air quality to make it burn more cleanly. Ethanol and methyl tertiary butyl ether (MTBE), a natural gas derivative, were the leading potential oxygenates. Lower-cost MTBE dominated the oxygenate market until leaks in underground storage tanks caused it to contaminate drinking water. Multiple states banned MTBE and ethanol became the default oxygenate.

Ethanol cemented its place as a gasoline additive in 2005 through the first renewable fuel standard, which mandated that 4 billion gallons (bgal) of ethanol be used in 2006 and steadily increased the requirement to 7.5 bgal per year by 2012. This 2012 quantity corresponded to 5% of projected domestic gasoline use in that year, up from the 4.6% market share held by oxygenates in 2005. Thus, the 2005 standard represented a negligible expansion of oxygenates in gasoline above the Clean Air Act requirement.

The RFS2, established in 2007, expanded the 2005 standard and set ambitious standards for biofuel use with the twin goals of reducing greenhouse gas (GHG) emissions and reducing dependence on foreign oil.

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[2] For a more detailed summary of this history, see Carter, Rausser and Smith (2017).

To address GHG emissions, the statute specifies that an increasing proportion of required biofuel be fuels with lower emissions than corn ethanol. To that end, it specifies four categories of biofuel:

1. cellulosic biofuel, which can be produced from the inedible parts of plants and must have at least 60% lower GHG emissions than petroleum;
2. biomass-based diesel, typically produced from oilseeds such as soybeans or canola, tallow, or used cooking oil, and must have at least 50% lower GHG emissions than petroleum;
3. other advanced biofuel, mostly ethanol produced from sugarcane but also any renewable fuels other than ethanol derived from corn that have at least 50% lower GHG emissions than petroleum; and
4. conventional biofuel, which is essentially corn ethanol, and must have at least 20% lower GHG emissions than petroleum.

To qualify under the RFS2, a biofuel needs to at least meet the category 4 standard. In addition to specifying the total required amount of biofuel each year, the statute specifies minimum amounts that must come from categories 1, 2, and 3.

The Environmental Protection Agency (EPA), which administers the RFS, may set the required biofuel volumes for any category below the mandate if there is insufficient supply. Table 1 shows both the volumes in the statute and the final volumes required by EPA each year to 2022. Firms can use above-mandate volumes of categories 1 and 2 fuel in lieu of categories 3 and 4, and they can use above-mandate volumes of category 3 fuel in lieu of category 4. Several features stand out in the table. First, cellulosic

Table 1: Mandated Renewable Fuel Use in the RFS2 by Category (bgal)

	Total		1. Cellulosic		2. Biodiesel		3. Other Advanced		4. Corn Ethanol	
	Statute	Final	Statute	Final	Statute	Final	Statute	Final	Statute	Final
2006	4.	4.							4.	4.
2007	4.7	4.7							4.7	4.7
2008	9.	9.							9.	9.
2009	11.1	11.1			0.8	0.8			10.3	10.3
2010	13.	13.	0.1	0.01	1.	1.			11.9	12.
2011	14.	14.	0.3	0.01	1.2	1.2			12.5	12.7
2012	15.2	15.2	0.5	0.01	1.5	2.3	0.	0.	13.2	12.9
2013	16.6	16.6	1.	0.01	1.5	1.9	0.3	0.8	13.8	13.8
2014	18.2	16.3	1.8	0.03	1.5	2.4	0.5	0.2	14.4	13.6
2015	20.5	16.9	3.	0.01	1.5	2.6	1.	0.3	15.	14.1
2016	22.3	18.1	4.3	0.23	1.5	2.9	1.5	0.5	15.	14.5
2017	24.	19.3	5.5	0.31	1.5	3.	2.	1.	15.	15.
2018	26.	19.3	7.	0.29	1.5	3.2	2.5	0.9	15.	15.
2019	28.	19.9	8.5	0.38	1.5	3.2	3.	1.3	15.	15.
2020	30.		10.5		1.5		3.		15.	
2021	33.		13.5		1.5		3.		15.	
2022	36.		16.		1.5		3.5		15.	

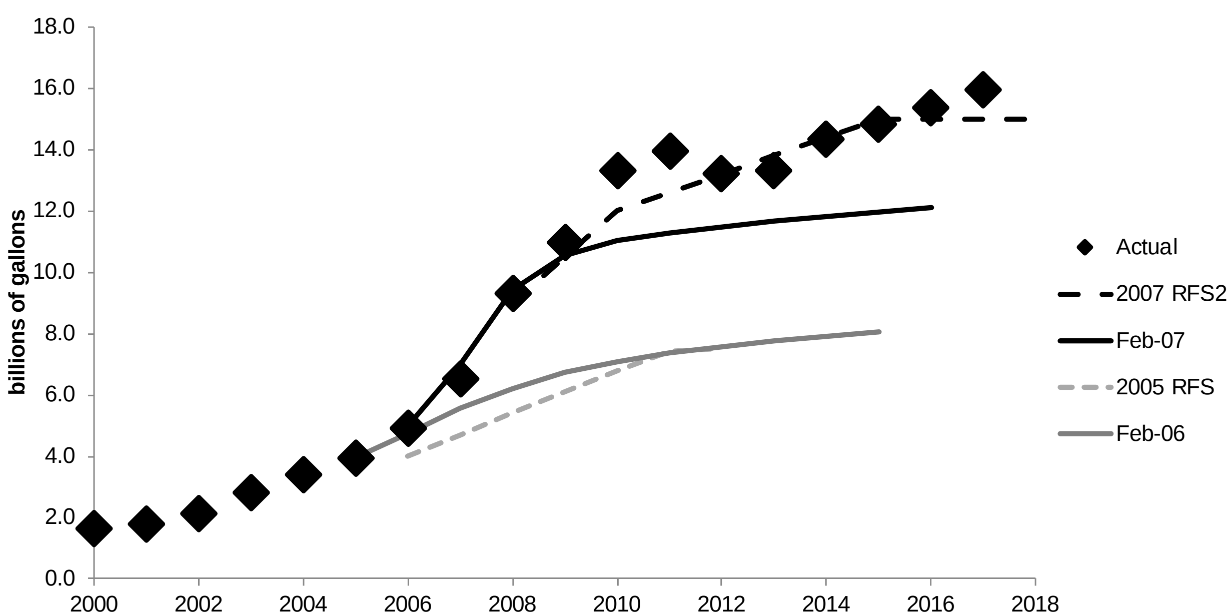
Note: Category 4 mandates defined as total minus 1, 2, and 3. The category 3 mandate is defined as the advanced biofuel mandate (not displayed) minus 1 and 2. Statute signifies volumes in the RFS statute and Final signifies final volumes set by EPA. Biodiesel volumes are displayed as 1.5 times the number of wet gallons because each gallon of biodiesel generates 1.5 renewable fuel credits (RINs). Source: EPA.

biofuels have not materialized as expected, which means that the promised GHG benefits of the RFS2 have not materialized. In 2019, the statute requires 8.5 bgal of cellulosic biofuel, but projected use is just 0.38 bgal. Moreover, this 0.38 bgal is almost all biogas produced from landfills and potentially used in natural gas vehicles, rather than ethanol to be used in internal combustion engines. Second, the quantity of corn ethanol required to meet the mandate tops out at 15 bgal, so its effect on agricultural markets should also top out. The statute requires no further expansion of corn ethanol after 2015. Third, EPA has increased biodiesel requirements substantially. Actual biodiesel use has exceeded the mandated quantities shown in the table as firms has chosen to use biodiesel (category 2) in place of other advanced biofuel (category 3).

Carter, Rausser and Smith (2017) estimate that the RFS2 increased required ethanol use by 5.5 billion gallons per year. To illustrate this, Figure 1 shows mandated and actual ethanol production since 2000 alongside projections made by the United States Department of Agriculture (USDA) in February 2006 and February 2007. The difference between the 2005 and 2007 RFS mandates started at 3.6 bgal of ethanol in 2008. It rose to 4.4 bgal in 2009 and averaged 5.4 bgal in the years 2010-2012.

USDA projected in February 2006 that ethanol production would be quite similar to the 2005 standard (see Figure 1). As noted earlier, this level would meet the oxygenate standard for reformulated gasoline under the Clean Air Act. However, a building boom in ethanol production capacity occurred in 2006. By the end of that year, enough ethanol production capacity was under construction to more than double production. Reflecting this building boom and the forthcoming RFS2, USDA's February 2007 projections jumped above its February 2006 projections. Agricultural firms observing this activity had an incentive for storage firms to increase corn inventory to be ready when this new capacity went into production. For this reason, we measure the effect of the 2007 RFS on grain markets beginning in late 2006.

Figure 1: Projected, Mandated and Actual Ethanol Production

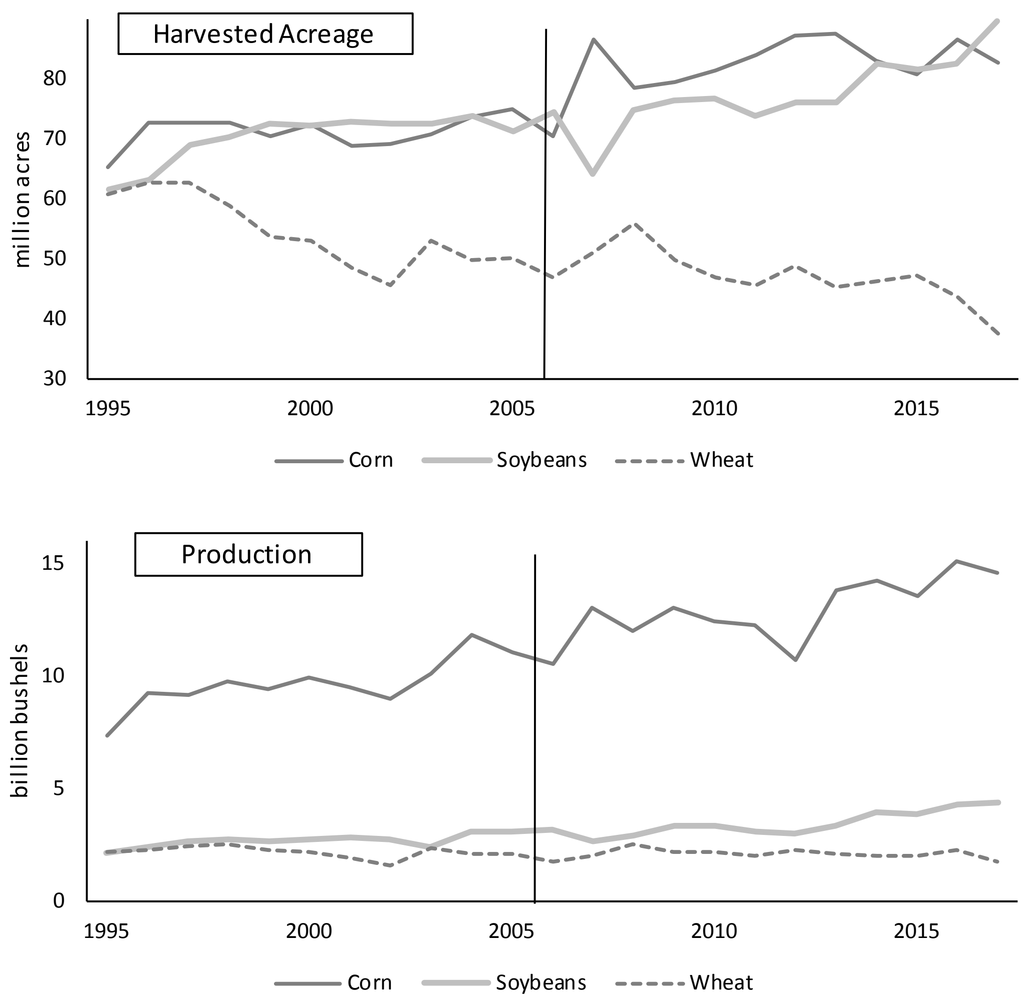


Corn, Soybeans and Wheat in the United States

The RFS2 affects corn, soybean and wheat markets in two ways. First, the mandated increase in ethanol and biodiesel production creates additional demand for corn and soybeans. Essentially all ethanol used in the US is produced from corn. Along with used cooking oil, other oilseeds such as canola, and tallow, soybeans are one of the feedstocks used to produce biodiesel. Second, the RFS2 increases demand for corn and soybeans, which causes farmers to plant more of those crops, leaving less land available for other crops.

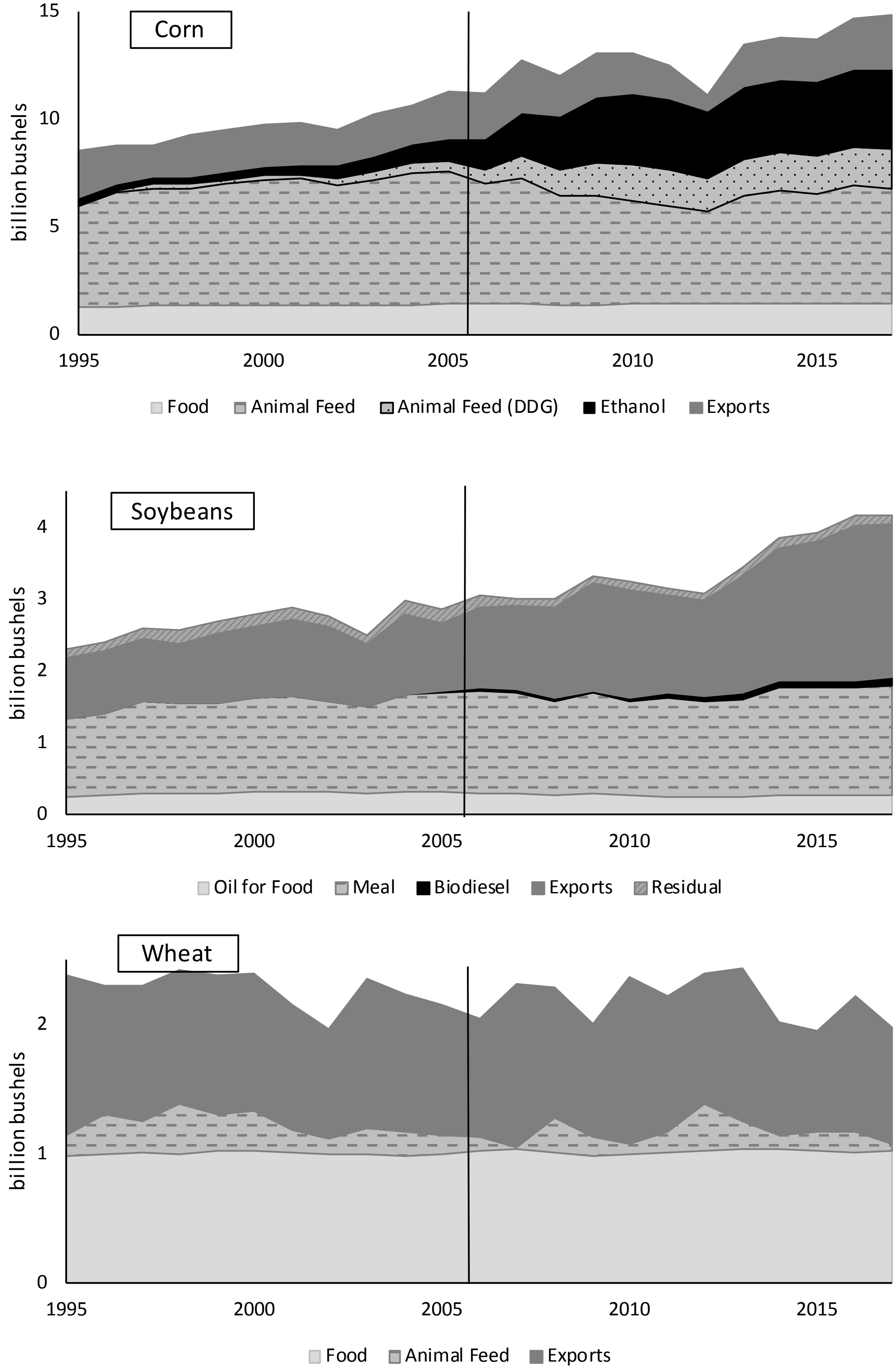
Production of corn, soybeans and wheat occupies about two thirds of US cropland. The top panel of Figure 2 shows harvested acreage of these three crops since 1995. In the mid-1990s, these crops occupied similar amounts of land. Since that time, corn and soybean acreage has increased and wheat acreage has declined. Corn acreage increased by 24% in 2007 as the expansion in the RFS loomed. Much of this increase was in central corn-belt states such as Iowa, Illinois and Indiana, where corn is typically rotated

Figure 2: Supply of Corn, Soybeans, and Wheat



Note: Vertical line at 2006 indicates which when 2007 RFS first affected grain markets. Source: USDA

Figure 3: Uses of Corn, Soybeans and Wheat in the US



Note: Vertical line at 2006 indicates which when 2007 RFS first affected grain markets. Source: USDA with soybeans (Hendricks, Smith and Sumner 2014). After some mean reversion in 2008, corn acreage remained high and increasing. From 2001-2005, average corn acreage was 1% below soybean acreage. From 2006-2010, average corn acreage exceeded soybean acreage by 8%. Soybean acreage recovered in the later years in response to increased demand for exports to China.

The bottom panel of Figure 2 shows a steady increase in corn production, aside from the 2012 drought, which affected corn production much more than soybeans or wheat. Soybeans produce fewer bushels per acre than corn and wheat, but soybean production increased steadily throughout the sample period, increasing from 2.2 billion bushels in 1995 to 4.4 billion bushels in 2017. Between 1995 and 2017, wheat acreage declined by 38%. Wheat production declined by 20% during the same period as increasing yields offset some of the acreage decline.

Figure 3 shows how corn, soybeans, and wheat have been used in the US since 1995. For corn, the dominant change is the increase in ethanol use. About one third of each corn kernel that enters an ethanol plant is recycled as dried distillers grains (DDG), which are used for animal feed and have a similar price to corn grain. The other two thirds of the kernel, the starch, are converted to ethanol. Figure 3 displays these two components separately; the black area in the figure (denoted "ethanol") is the net amount of corn used for ethanol. The amount of corn used for food is relatively constant over the period.3 With the exception of the 2012 drought year, the quantity exported is also relatively constant.

Soybean exports grew by a factor of 2.5 over the period in Figure 3. By 2017, half of all US soybeans were exported. Much of this demand came from China, which consumed 22% of the world's soybeans in 2017, up from 8% in 1995. This increase in demand for soybeans created upward pressure on soybean prices in addition to the pressure from the RFS.

Almost all domestically consumed soybeans are crushed before use, i.e., they are processed into oil and meal. Soybean meal is used predominantly as an animal feed and oil is used for human consumption or to make biodiesel. By weight, about 80% of each bean becomes meal and the other 20% becomes oil. Given that most of the soybean becomes meal and half of soybeans are exported, the proportion of US soybeans by weight that end up as soybean oil is small, as illustrated in Figure 3. Thus, even though 30% of soybean oil was used to make biodiesel in 2017, less than 3% of soybeans ended up in biodiesel.[4]

Most wheat is either exported or used domestically for food, with a small amount used for animal feed. The quantity used for food is relatively constant from year to year, which implies that exports and animal feed demand is much more elastic and it is these areas that adjust to accommodate fluctuations in production.

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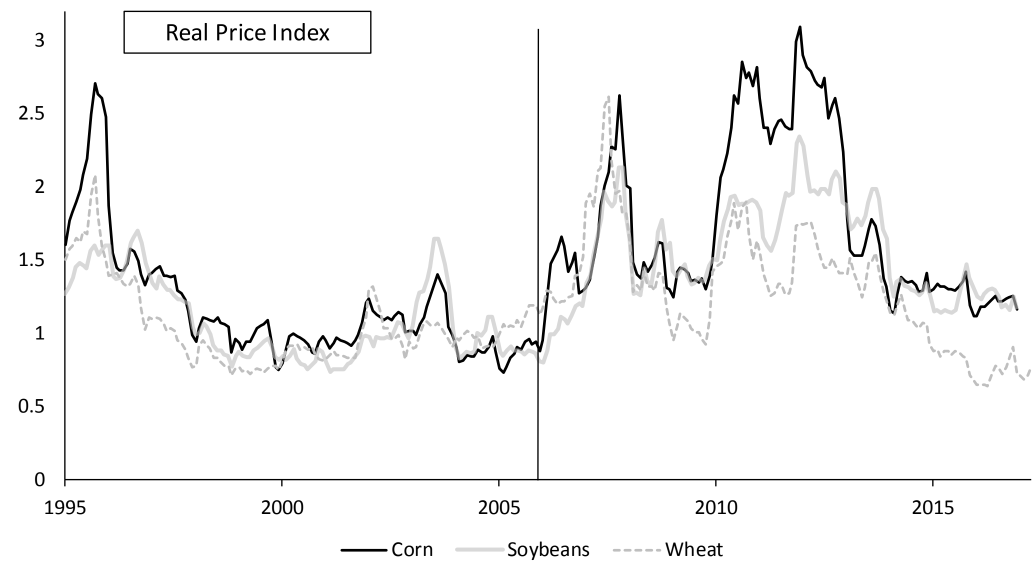
[3] The food category for corn and wheat also includes seed and industrial uses. These two categories are included in the residual category for soybeans.

[4] Soybean oil prices are typically about double soybean meal prices, so biodiesel would be more prominent in Figure 3 if I displayed the quantities by dollar value rather than by weight. Either way, biodiesel is a relatively minor source of demand for soybeans.

Figure 4: Real Price Indexes for Corn, Soybeans and Wheat in the US



Note: Monthly prices deflated using US CPI for all items and indexed to average one across the 2001-2005 crop years. Corn and soybean prices are Central Illinois cash bids. Wheat prices are Kansas City hard red winter cash bids. Vertical line at 2006 indicates which when 2007 RFS first affected grain markets. Time is denoted by crop year, e.g., the label 1995 denotes September 1 of that year. Source: USDA

Figure 4 shows an index of monthly real prices for the three commodities. The corn price increased by about 50% in fall 2006 and has remained at or above that level since. In the first five years after the RFS hit the markets (Sept 2006 – Aug 2011), corn prices were up 77%, soybean prices up 62% and wheat prices up 62% relative to the last five pre-RFS years (Sept 2001 – Aug 2006).

To ascertain how much of these prices increases can be attributed to the RFS2, we need to estimate a model that controls for other factors. All prices spiked around the 2008 commodity boom for reasons related more to the business cycle and global commodity demand than the RFS2. Prices spiked again in 2010-2012 as relatively poor yields, especially for corn, coincided with high demand for biofuels due to the RFS and for soybean exports to China. Prices came back from these peaks after the 2012 drought.

To summarize this section, the two largest recent trends in these markets since 2006 been higher prices, increasing corn use for ethanol, and increasing soybean exports. In the next section, I describe the model I use to estimate the effects of the 2007 RFS on corn, soybean and wheat prices.

Method

I apply the method in Carter, Rausser and Smith (2017), who use a partially identified structural vector autoregression model to estimate the effect of the RFS2 on corn prices. I update their model for corn with data through the 2016-17 crop year, and I apply the model to soybeans and wheat. Here, I provide a brief summary of the model.

Carter, Rausser and Smith's model incorporates the fact that the RFS2 is a persistent rather than a transitory shock to agricultural markets. This distinction is important because persistent shocks have larger price effects than transitory shocks. The market can respond to a 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, the model uses data on inventory levels and on the term structure of futures prices.

Table 2 summarizes the data used to estimate the model. It includes global real economic activity, which is an important driver of commodity prices.[5] To represent global economic activity, Carter, Rausser and Smith use the index developed by Kilian (2009) from dry-cargo shipping rates. 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" (pg. 1056).

The timeline at the bottom of Table 2 shows when the variables are measured. I measure inventory (I) at the end of the crop year. The real economic activity index (X), the futures price (F), and the spot price (S) are all measured at the same point in the middle of the crop year, i.e., in the month of March, which is after the previous crop has been harvested and before the new crop is planted.[6] The arrow indicates that the futures price is the contract for delivery in November or December, which is after the next harvest.

Carter, Rausser and Smith use the futures and spot prices to compute the convenience yield, which is essentially the spot price minus the futures price.[7] Convenience yield provides crucial information for identifying the differing effects of transitory and permanent shocks. For example, in response to poor growing season weather, the spot price increases and inventory decreases, but the futures price does not increase much because traders understand that supplies will be replenished by the new harvest before the futures contract delivers. In such cases, the convenience yield increases. In contrast, persistent shocks such as the RFS2 cannot be met by drawing down inventory, so spot and futures prices increase by similar amounts and the convenience yield does not increase. Observing both the spot and futures price allows them to be identified separately, whereas observing only one price for a commodity does not.

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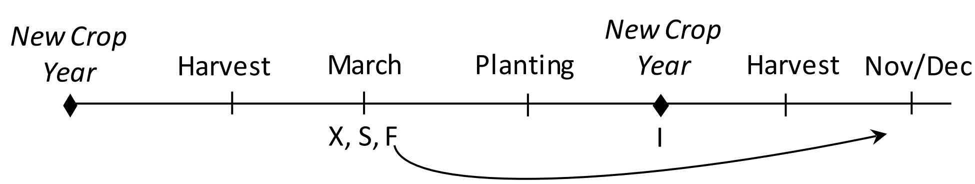
[5] Carter, Rausser and Smith (2011) show that both the 1973–74 and 2007–08 commodity booms were preceded by unusually high world economic growth, especially in middle-income countries.
[6] Winter wheat is the exception, as it is planted late in the fall of the previous year.
[7] In computing the convenience yield, I adjust the spread for interest and warehousing costs as in equation (13) of Carter, Rausser and Smith (2017).

Table 2: Data Used in Model

		Corn	Soybeans	Wheat
Global Commodity Demand (X)	variable	Real economic activity index	Real economic activity index	Real economic activity index
	Source	Kilian (2009)	Kilian (2009)	Kilian (2009)
	timing	March	March	March
Inventory (I)	variable	Total ending stocks (bu)	Total ending stocks (bu)	Total ending stocks (bu)
	source	USDA	USDA	USDA
	timing	September	September	June
Futures Price (F)	variable	CBOT Dec contract	CME Nov contract	CBOT Dec contract (1960-1976), KCBOT Dec contract (1977-2017)
	source	quandl	quandl	quandl
	timing	average daily price in March	average daily price in March	average daily price in March
Spot Price (S)	variable	Central IL cash bid	Central IL cash bid	St Louis SRW cash bid (1960-1976), Kansas City HRW cash bid (1977-2017)
	source	USDA AMS	USDA AMS	USDA AMS
	timing	average daily price in March	average daily price in March	average daily price in March

Annual Timeline



Note: All variables measured annually from 1960 – 2017. All prices deflated by the March CPI for all items. The price and inventory variables enter the model in logs.

Unlike corn and soybeans, which are relatively homogeneous, there are several different classes of wheat produced in the United States. They vary by where they are grown, the growing season, hardness, and protein content. Hard red winter (HRW) wheat makes up 40-45% of production in a typical year. It is grown mostly in and around Kansas, and is planted in the fall for harvest in early summer. Hard red spring (HRS) wheat makes up about 25% of production in a typical year and is considered the highest quality class due to its high protein content. It is grown in the northern plain states, and is planted in the spring for harvest in the late summer. Soft red winter (SRW) wheat makes up about 20% of production and most of the rest is white wheat. Robust futures markets exist for HRW in Kansas City, HRS in Minneapolis, and

SRW in Chicago. The SRW futures market has a long history and remains the most actively traded, even though it lags behind the other two in production. The HRW and HRS futures markets are newer and only report viable prices beginning in the late 1970s. In my analysis, I use SRW prices until March 1976, after which I switch to HRW prices. HRW and HRS futures prices. The results are the same if I instead use a weighted average of the three prices after 1976.

Estimating the incremental effect of RFS2 requires an estimate of ethanol use that would have occurred in the absence of RFS2. This business-as-usual quantity depends on factors that are difficult to quantify, including the true value of ethanol to the fuel industry and the extent to which, by guaranteeing demand for ethanol, the RFS2 caused large capital investment in ethanol plants and fueling infrastructure.

For each commodity, I follow the procedure in Carter, Rausser, and Smith (2017). I fit the model using data prior to the 2006 crop year and use it to project business-as-usual (BAU) prices that would have occurred after 2006 in the absence of RFS2. Specifically, I estimate business-as-usual prices by simulating from the model what prices would have been if the markets had experienced the same shocks to (i) real economic activity, (ii) US production, (iii) Chinese soybean imports, and (iv) the supply of grain storage that we experienced post 2006, but no other shocks.[8] The average difference between observed prices and these simulated BAU prices provides an estimate of how much the RFS2 affected prices.

Table 3: Observed vs Business-as-Usual Spot Prices

	Corn		Soybeans		Wheat	
Dollars per bushel						
2001-2005	2.15		5.96		4.03	
2006-2010						
Observed	3.81		9.67		6.52	
BAU	2.90		8.11		5.45	
(80% CI for BAU)	2.41	3.33	6.22	9.47	4.39	5.97
2006-2010 percent increase relative to …						
… 2001-2005	77%		62%		62%	
… BAU	31%		19%		20%	
(80% CI for BAU)	58%	14%	55%	2%	49%	9%

Note: The business-as-usual prices are produced from the model in Carter, Rausser and Smith (2017) with data through the 2016-17 crop year. The model projects the natural log of prices. To obtain the BAU value, I took the average projected difference between the observed and BAU log prices during 2006-2010. These differences were 0.27 for corn, 0.18 for soybeans, and 0.20 for wheat, which correspond to 31%, 19%, and 20% respective differences and imply that the observed prices were 31%, 19%, and 20% above the BAU for the three commodities. The point estimates come from the point identified parameters in the model and the confidence intervals are generated from the identified set. Both are displayed in the appendix.

[8] Garcia, Irwin and Smith (2015) show significant decreases in convenience yield since 2006, especially for wheat. Allowing observed post-2006 convenience yield shocks (supply of storage) to enter the BAU simulation reduces the estimated effect of RFS2 on wheat prices by 2 percentage points.

Results

I estimate the effects of the RFS2 on corn, wheat and soybean prices, by comparing observed prices in the 2006-2010 crop years to the BAU projections for those years. Table 3 shows that corn prices exceeded the BAU by 31%, soybean prices by 19% and wheat prices by 20% in 2006-2010. These estimates include 80% confidence intervals of [14%, 58%] for corn, [2%, 55%] for soybeans, and [9%, 49%] for wheat. Thus, there is a wide range of plausible price effects in the model, but the point estimates round to 30% for corn and 20% for soybeans and wheat.

Figure 5 shows the observed and BAU prices for the 2006-2016 crop years.[9] The vertical bars are 80% confidence intervals that capture uncertainty in the identified set for the model parameters. The parameters are estimated using data from the 1961-2005 crop years and so are subject to sampling error.

Corn prices jumped in 2006 and increased further in 2007 as corn traders stored additional corn in preparation for the impending ethanol boom.[10] BAU prices also increase during this period due to strong global commodity demand. The relative effect of the RFS2 was lower than average in the 2008 and 2009 crop years as the financial crisis and the corresponding crash in oil prices and gasoline demand caused a drop in demand for corn from ethanol producers. Then in 2010 and 2011, along with worse-than-expected crop yields, increasing ethanol demand caused corn prices to rise again significantly above the BAU values. In these two years, we estimate that corn prices were more than 50% higher than they would have been without the RFS2-induced shocks.

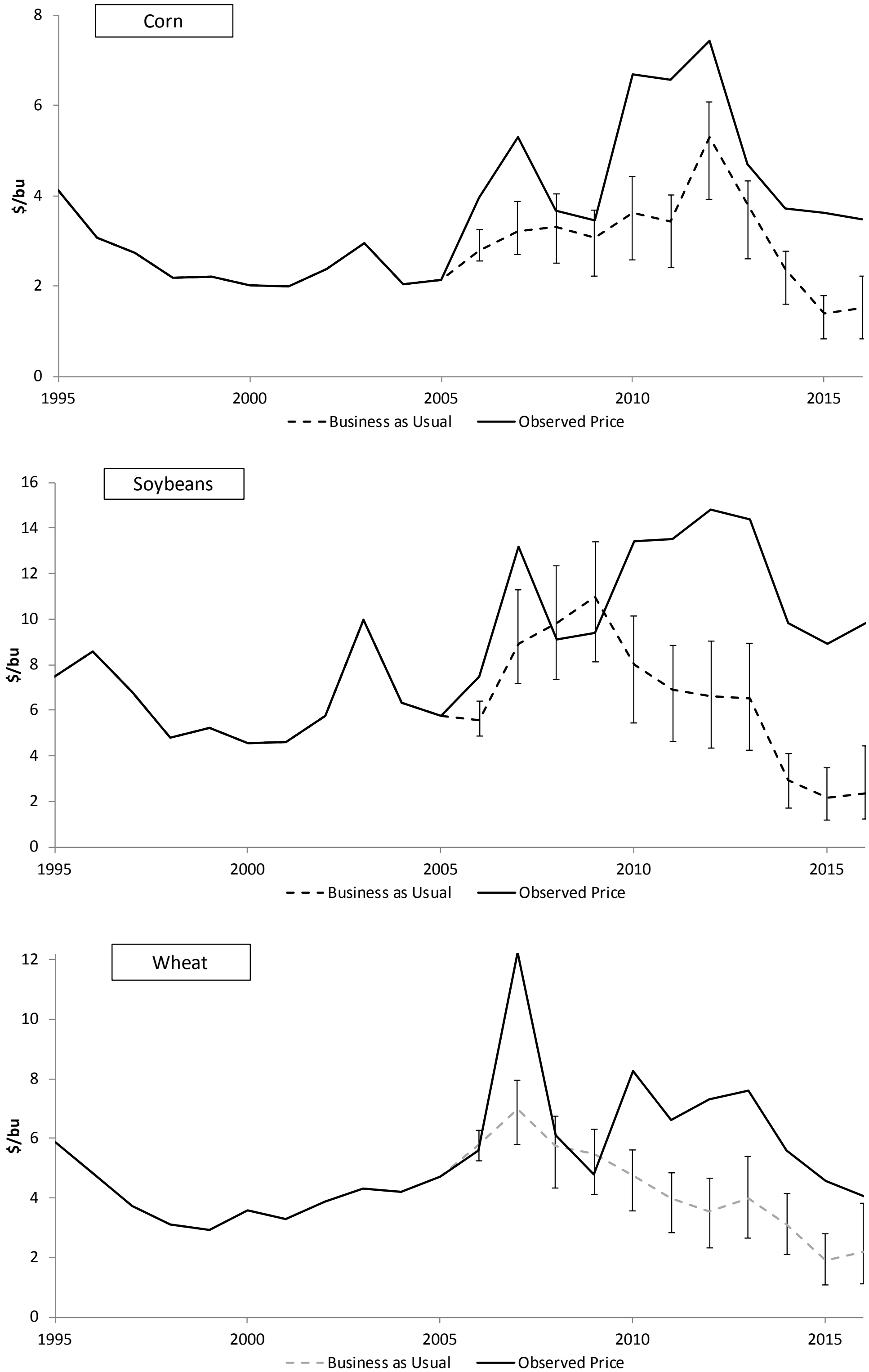
In the BAU world, the market would have run corn inventory down in 2010 and 2011, making the market more vulnerable to the 2012 drought than occurred in actuality. In the real world, the presence of persistent high ethanol demand prevented inventories from being run down too much and thus made the market more resilient entering the 2012 crop year. As a result, the drought hit BAU corn prices harder than observed prices. The observed 2012 spot price is 30% above the BAU price. Good weather since 2014 has produced large crops, so corn prices have declined from their peak values, but these declines also occur in the BAU scenario.

The patterns for corn are mirrored in soybeans and wheat, especially in the 2006 to 2010 period. The 2012 drought had much smaller effects on these commodities than on wheat. There was a relatively small yield decline for soybeans and a yield increase for wheat in that year, so the BAU price does not spike for them like it does for corn. In the last few years, both the observed and BAU prices declined.

[9] The appendix contains detailed output from the model corresponding to the output presented in Table 2-3 and Figures 5-7 of Carter, Rausser, and Smith (2017). Note that the model contains two distinct identifying assumptions, one that provides point identification and one that provides set (partial) identification. Because the assumptions differ, there is no reason that the point identified parameter should lie within the identified set. In all cases, the estimated prices effects are very similar whether I use the point estimate or the identified set.

[10] Years refer to crop years. Thus, a price jump in 2006 refers to the 2006-2007 crop year and therefore to a price for the crop harvest in fall 2006, which we measure in March 2007.

Figure 5: Observed and Business-as-Usual Spot Prices



Note: The business-as-usual prices are produced from the point-identified parameters in the model in Carter, Rausser and Smith (2017), which are fit to data for the 1961-2005 crop years separately for each commodity. Each year denotes a crop year, e.g., 2006 is Sep 2006 through Aug 2007 for corn and soybeans and June 2006 through May 2007 for wheat. Vertical bars are 80% confidence intervals.

The BAU projections become less credible as time passes. These projections assume only four sources of price shocks, and other potential sources of shocks became apparent after 2010. In particular, a severe drought in South America reduced soybean production from Argentina and Brazil in the 2011 crop year (i.e., the harvest that occurred in the early part of calendar year 2012). These two countries produce half of the world's soybeans. This event pushed soybeans prices up significantly, but it is not accounted for in the BAU projections. As a result the BAU soybean prices after 2011 may be too low.

Similarly for wheat, the 2012 drought caused an increase in the demand for wheat for animal feed due to the reduction in available corn. As a result, wheat prices rose. This shock is not included in the BAU projection, so the BAU wheat prices after 2011 may be too low. Thus, if we were to estimate the effect of the RFS by averaging all years from 2006-2016, we would obtain estimates for soybeans and wheat that are larger than 20%, but are likely biased upwards.

Carter, Rausser, and Smith (2017) report an alternative estimate of the effect of the RFS2 on corn prices. They impose a permanent demand shift 1.3 billion bushels on the model and find a new equilibrium with prices 31% higher prices (90% confidence interval [0.05, 0.95]). This 1.3 billion bushel corn demand increase is equivalent to 5.5 billion additional gallons of ethanol, which is the posited incremental effect of the RFS2. The similarity of this estimate to the one in Table 3 provides support for the BAU method.

Conclusion

The RFS2 expanded ethanol production by about 5.5 bgal over business as usual. Here, business as usual is defined as the amount of ethanol required to meet the standards for reformulated gasoline under the 1990 Clean Air Act, an amount that was codified in the 2005 renewable fuel standard. The RFS2 first hit agricultural markets in the 2006-07 crop year as firms began to store additional corn in preparation for the impending ethanol boom.

Using the new econometric model of Carter, Rausser and Smith (2017), I estimate that the RFS2 raised corn prices by 30%, and it raised soybean and wheat prices by 20% each. These estimates include 80% confidence intervals of [14%, 58%] for corn, [2%, 55%] for soybeans, and [9%, 49%] for wheat.

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TECHNICAL APPENDIX

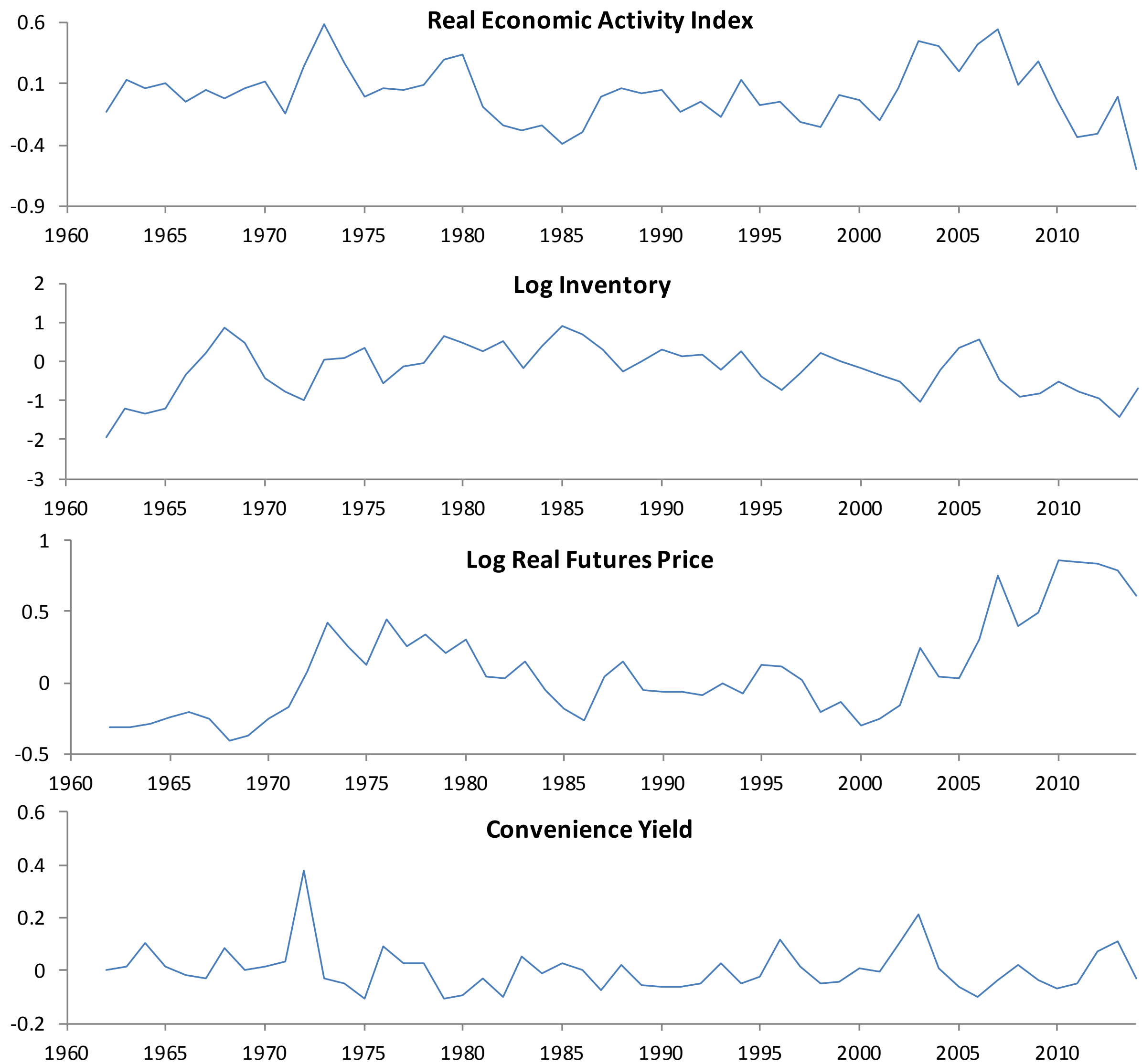
This appendix contains the model output for soybeans and wheat that is presented for corn in Carter, Rausser and Smith (CRS, 2017). For comparison, I denote the analogous table in CRS.

Soybean VAR Parameter Estimates (cf Table 2 in CRS)

Equation	*REA*	*Inventory*	*Futures*	*Conv. Yield*
	Reduced Form Estimates: $A^{-1}B_1$			
REA_{t-1}	0.52* (0.12)	-0.24 (0.29)	0.04 (0.11)	-0.07 (0.06)
$Inventory_{t-1}$	-0.02 (0.04)	0.71* (0.11)	0.04 (0.04)	-0.04* (0.02)
$Futures_{t-1}$	-0.04 (0.10)	0.90* (0.30)	0.71* (0.10)	-0.06 (0.04)
$Conv.\ Yield_{t-1}$	0.86* (0.26)	1.87* (0.53)	0.33 (0.44)	-0.01 (0.11)
Constant	0.11 (0.36)	-0.20 (1.16)	0.37 (0.30)	0.60 (0.19)
Trend	0.000 (0.003)	0.035* (0.013)	-0.011* (0.004)	0.000 (0.001)
	A Matrix: imposing $\alpha_{23} = 4.4 - 1/(\alpha_{32} + \alpha_{42}(1+\alpha_{34}))$			
REA	1	0	0	0
Inventory Supply	0.65	1	-0.50	-0.50
Inventory Demand	-0.44	0.17	1	-0.12
Supply of Storage	-0.10	0.09	0	1
	A Matrix: Identified Set			
REA	1	0	0	0
Inventory Supply	[0.49, 3.04]	1	[-4.25,-0.25]	[-4.25,-0.25]
Inventory Demand	[-0.44,-0.37]	[0.15, 0.24]	1	[-0.46, -0.16]
Supply of Storage	[-0.10, -0.08]	[0.09, 0.15]	0	1
	A Matrix: >90% Confidence Interval			
REA	1	0	0	0
Inventory Supply	[-0.04, 4.89]	1	[-6.60, -0.25]	[-6.60, -0.25]
Inventory Demand	[-0.52,-0.25]	[0.09, 0.30]	1	[-0.93, 0.12]
Supply of Storage	[-0.18, 0.02]	[0.05, 0.22]	0	1

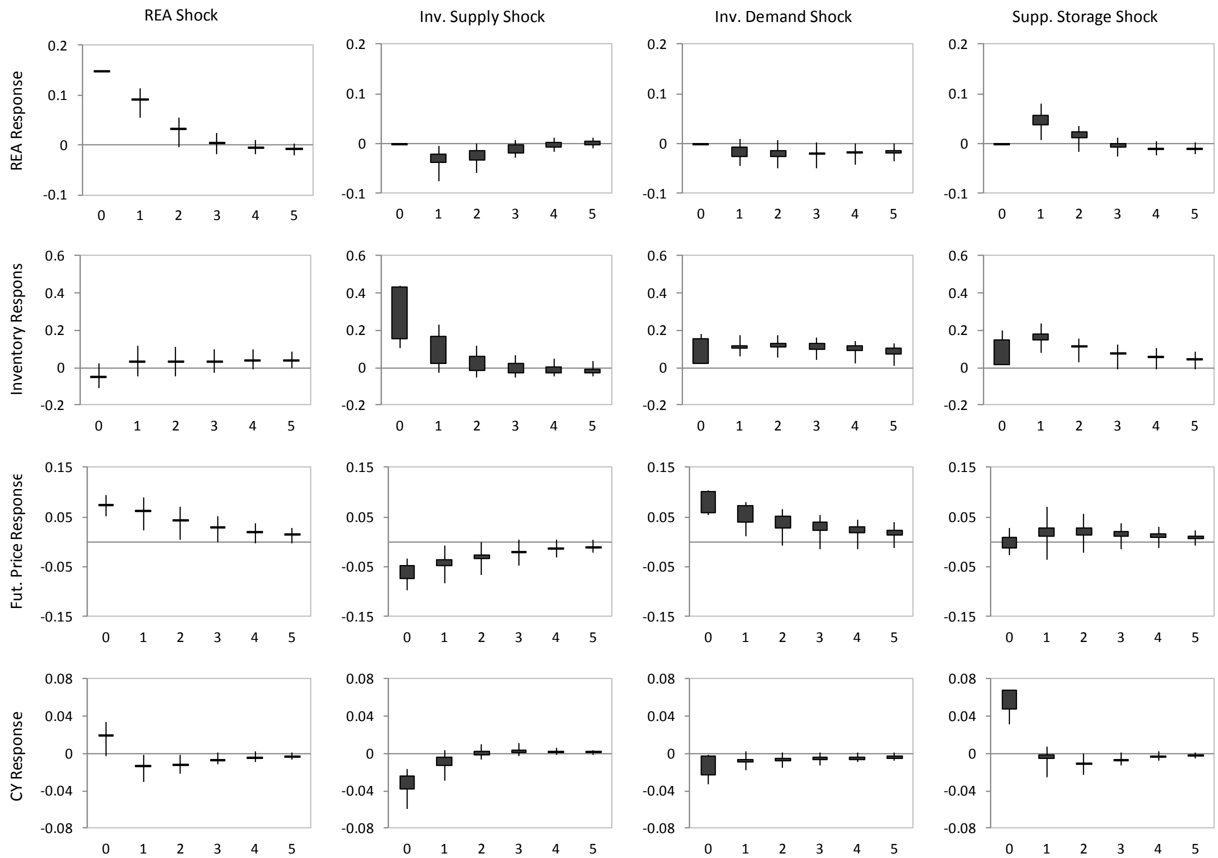
Note: Sample range: 1961–2005; standard errors in parentheses; * indicates significance at 5%; model selection criteria values are AIC_C=-648.86 and BIC=-620.31; for the two-lag model, we obtain AICc = -640.24 and BIC = -583.15, so the one-lag model is favored. We obtain the confidence intervals using a recursive-design wild bootstrap (see footnote 21 of CRS).

Detrended Data for Key Variables in Soybean Model (cf Figure 5 in CRS)



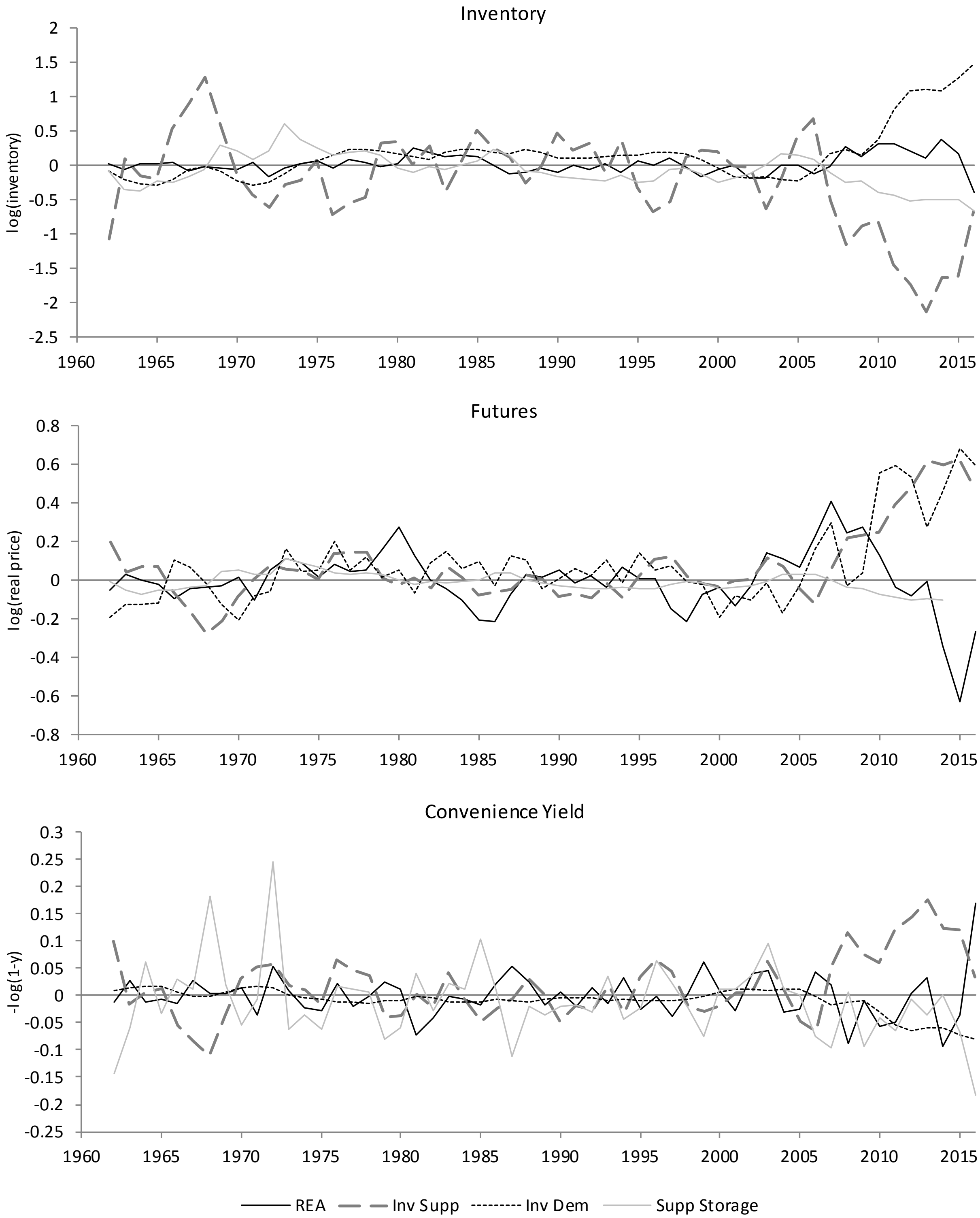
Note: For clarity, this figure shows linearly de-trended series, where we estimate the trend in the pre-RFS2 period (1961-2005). For the VAR estimation, we use the actual series and include a constant and linear trend in each equation of the model.

Impulse Response Functions for Soybeans (cf Figure 6 in CRS)



Note: Responses to one-time one-standard-deviation shocks for the two-lag model. 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 in CRS).

Historical Decomposition for Soybeans (cf Figure 7 in CRS)



Note: Figures show contributions of each shock to the relevant series for the one-lag model. The sum of the contributions equals the observed data (net of trend).

Log Difference Between Actual and Counterfactual for Soybeans (cf Table 3 in CRS)

	2006-07	2007-08	2008-09	2009-10	2010-11	Average
No Inventory-Demand Shocks						
Inventory	0.61	-0.28	-0.85	-0.66	-0.35	-0.31
Fut. Price	0.09	0.39	0.22	0.29	0.82	0.36
Conv. Yield	-0.06	0.04	0.10	0.06	0.03	0.03
Cash Price	0.04	0.43	0.31	0.35	0.85	0.40
No Inventory-Demand or -Supply Shocks						
Inventory	0.61	-0.28	-0.85	-0.66	-0.35	-0.31
Fut. Price	0.09	0.39	0.22	0.29	0.82	0.36
Conv. Yield	-0.06	0.04	0.10	0.06	0.03	0.03
Cash Price	0.04	0.43	0.31	0.35	0.85	0.40
No Inventory-Demand Shocks						
Inventory-Supply Shocks from Production and China-Import Surprises Only						
Inventory	-0.19	0.12	0.56	0.89	0.58	0.39
Fut. Price	0.24	0.36	-0.03	-0.07	0.51	0.20
Conv. Yield	0.02	-0.01	-0.04	-0.08	-0.04	-0.03
Cash Price	0.26	0.36	-0.07	-0.14	0.47	0.18
No Inventory-Demand Shocks (80% confidence band)						
Inventory-Supply Shocks from Production and China-Import Surprises Only						
Inventory	-0.39 0.02	-0.19 0.49	-0.01 0.96	0.11 1.31	-0.34 1.04	-0.12 0.71
Fut. Price	0.15 0.33	0.18 0.53	-0.23 0.23	-0.25 0.21	0.30 0.84	0.04 0.42
Conv. Yield	-0.02 0.07	-0.06 0.05	-0.10 0.00	-0.15 -0.02	-0.10 0.02	-0.07 0.01
Cash Price	0.14 0.38	0.14 0.55	-0.28 0.19	-0.32 0.13	0.26 0.81	0.01 0.40
Identified Set						
No Inventory-Demand Shocks						
Inventory-Supply Shocks from Production and China-Import Surprises Only						
Inventory	-0.26 0.34	0.11 0.12	-0.06 0.65	0.30 0.99	0.21 0.68	0.18 0.43
Fut. Price	0.18 0.24	0.34 0.37	-0.02 0.02	-0.04 0.01	0.54 0.57	0.22 0.23
Conv. Yield	-0.05 0.02	-0.01 0.01	-0.05 0.05	-0.08 -0.03	-0.05 -0.02	-0.03 -0.01
Cash Price	0.13 0.27	0.34 0.37	-0.07 0.07	-0.12 -0.02	0.49 0.55	0.19 0.22
Identified Set (>80% confidence band)						
No Inventory-Demand Shocks						
Inventory-Supply Shocks from Production and China-Import Surprises Only						
Inventory	-0.46 0.55	-0.22 0.48	-0.65 1.06	-0.43 1.40	-0.64 1.14	-0.32 0.75
Fut. Price	0.09 0.33	0.17 0.54	-0.22 0.29	-0.23 0.28	0.31 0.88	0.06 0.44
Conv. Yield	-0.09 0.07	-0.06 0.06	-0.10 0.10	-0.16 0.02	-0.11 0.03	-0.07 0.03
Cash Price	0.01 0.38	0.15 0.56	-0.28 0.34	-0.31 0.24	0.27 0.86	0.02 0.44
Production Surprises (MMT)						
Actual Prod.	87.0	72.9	80.7	91.5	90.7	
May Forecast	83.8	74.7	84.5	87.0	90.1	
Surprise	3.2	-1.8	-3.8	4.5	0.6	
China Import Surprises (MMT)						
Actual Imports	28.7	37.8	41.1	50.3	52.3	
May Forecast	31.5	34.5	35.5	38.1	49.0	
Surprise	-2.8	3.3	5.6	12.2	3.3	
Total Surprise	6.0	-5.2	-9.4	-7.7	-2.8	

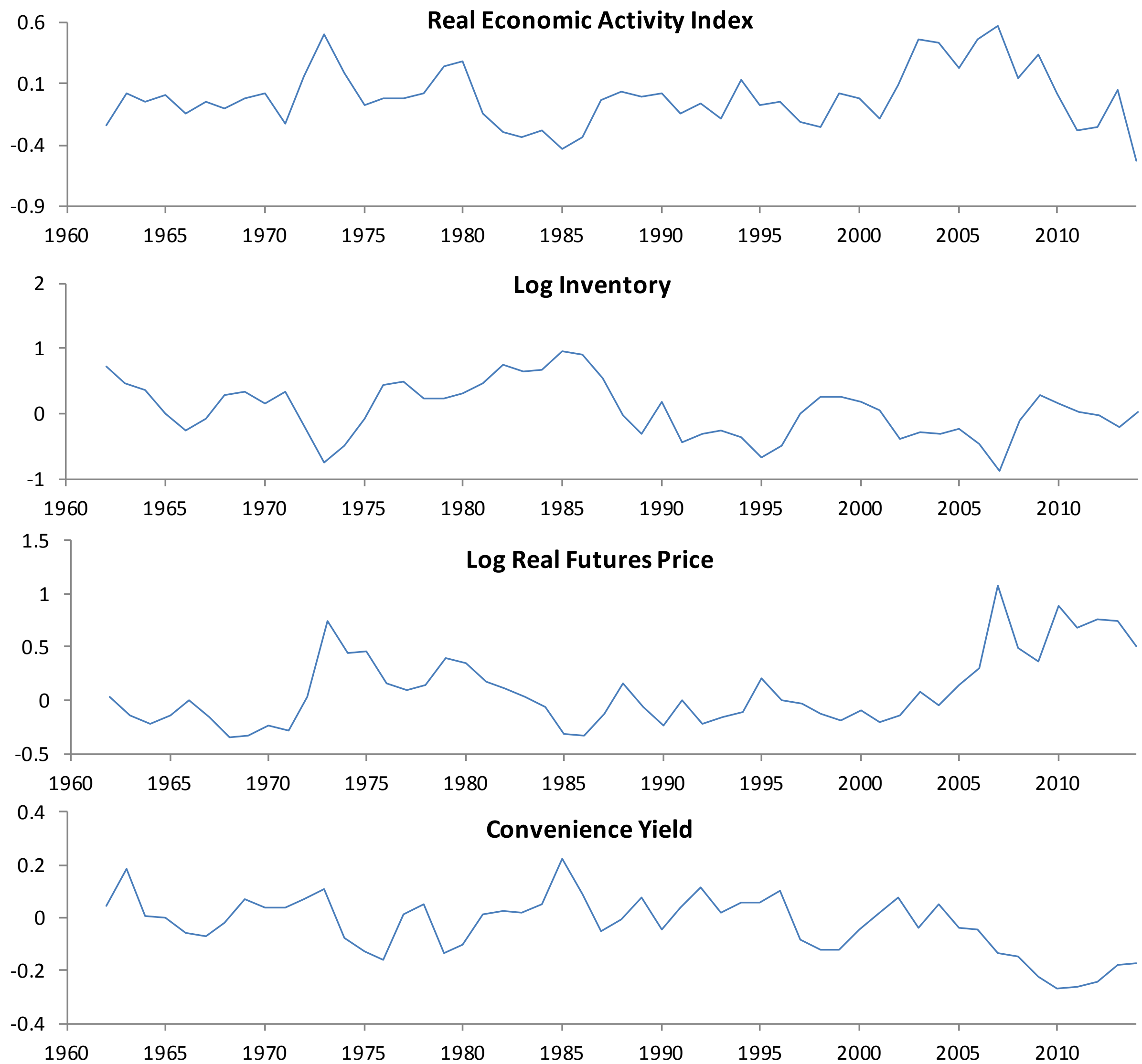
Note: Here we define the log cash price as log futures plus convenience yield. Table entries are results from the BAU calculations described in the text. Total surprise is production surprise minus China import surprise. Surprise terms divided by 6.6 MMT, which is average soybean inventory from 1996-2005. Because the identifying assumptions differ slightly, there is no requirement that the point identified parameters lie in the identified set.

Wheat VAR Parameter Estimates (cf Table 2 in CRS)

Equation	*REA*	*Inventory*	*Futures*	*Conv. Yield*
	Reduced Form Estimates: $A^{-1}B_1$			
REA_{t-1}	0.59* (0.14)	-0.51* (0.19)	0.42* (0.15)	-0.02 (0.07)
$Inventory_{t-1}$	-0.05 (0.07)	0.71* (0.09)	0.07 (0.06)	0.04 (0.04)
$Futures_{t-1}$	-0.16 (0.10)	0.58* (0.17)	0.53* (0.10)	-0.05 (0.05)
$Conv. Yield_{t-1}$	0.01 (0.24)	-0.10 (0.38)	0.18 (0.28)	0.31* (0.13)
Constant	0.85 (0.77)	1.80 (1.11)	0.17 (0.69)	-0.21 (0.37)
Trend	-0.005 (0.004)	0.016* (0.006)	-0.014* (0.004)	0.001 (0.002)
	A Matrix: imposing $\alpha_{23} = 4.4 - 1/(\alpha_{32} + \alpha_{42}(1+\alpha_{34}))$			
REA	1	0	0	0
Inventory Supply	2.11	1	-3.44	-3.44
Inventory Demand	0.04	0.81	1	0.44
Supply of Storage	0.11	0.16	0	1
	A Matrix: Identified Set			
REA	1	0	0	0
Inventory Supply	[0.71, 1.25]	1	[-1.47,-0.25]	[-1.47,-0.25]
Inventory Demand	[-0.16,-0.04]	[0.48, 0.68]	1	[0.56, 0.64]
Supply of Storage	[0.09, 0.10]	[0.12, 0.14]	0	1
	A Matrix: >90% Confidence Interval			
REA	1	0	0	0
Inventory Supply	[0.42, 1.72]	1	[-1.82, -0.25]	[-1.82, -0.25]
Inventory Demand	[-0.29,0.15]	[0.35, 0.78]	1	[0.20, 0.95]
Supply of Storage	[0.02, 0.20]	[0.07, 0.20]	0	1

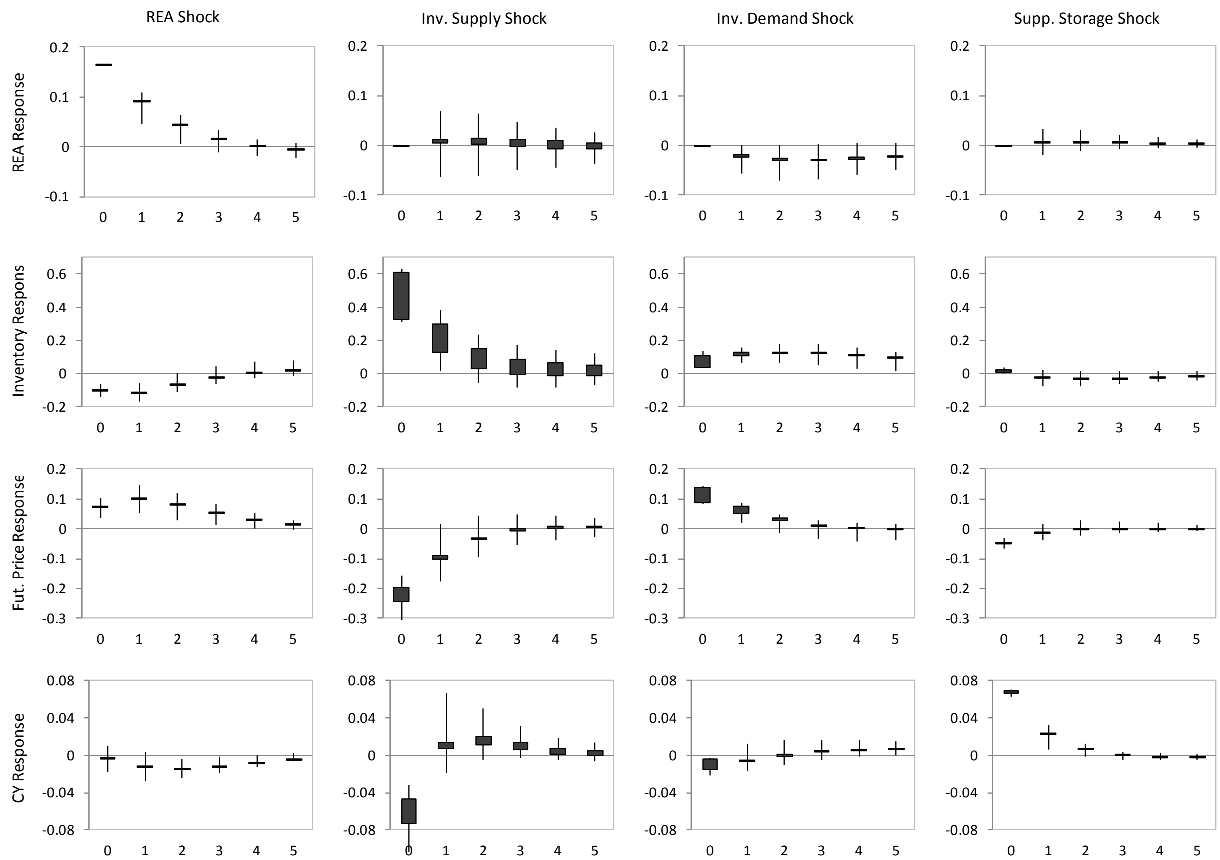
Note: Sample range: 1961–2005; standard errors in parentheses; * indicates significance at 5%; model selection criteria values are AIC_C=-648.86 and BIC=-620.31; for the two-lag model, we obtain AICc = -640.24 and BIC = -583.15, so the one-lag model is favored. We obtain the confidence intervals using a recursive-design wild bootstrap (see footnote 21 of CRS).

Detrended Data for Key Variables in Wheat Model (cf Figure 5 in CRS)



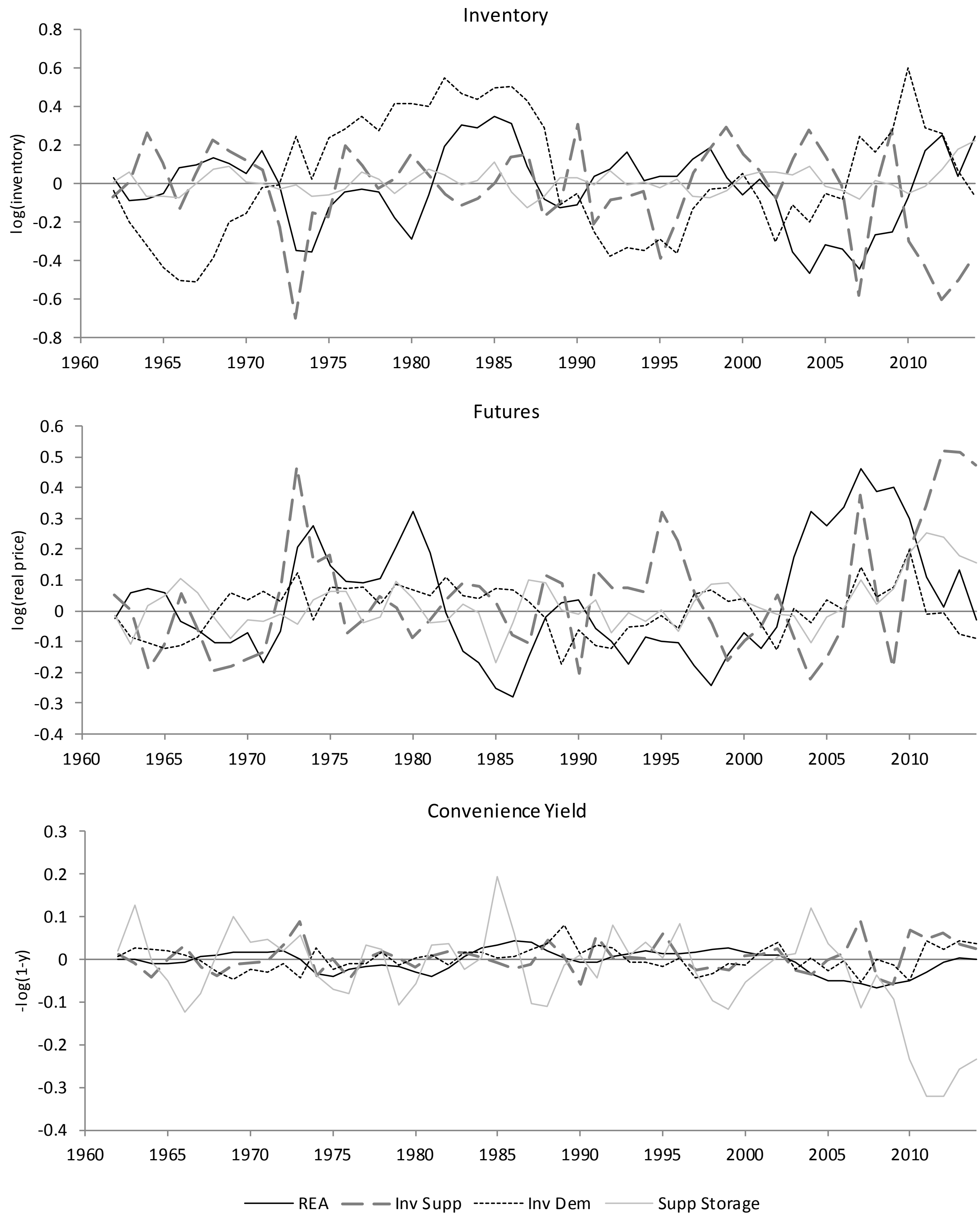
Note: For clarity, this figure shows linearly de-trended series, where we estimate the trend in the pre-RFS2 period (1961-2005). For the VAR estimation, we use the actual series and include a constant and linear trend in each equation of the model.

Impulse Response Functions for Wheat (cf Figure 6 in CRS)



Note: Responses to one-time one-standard-deviation shocks for the two-lag model. 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 in CRS).

Historical Decomposition for Wheat (cf Figure 7 in CRS)



Note: Figures show contributions of each shock to the relevant series for the one-lag model. The sum of the contributions equals the observed data (net of trend).

Log Difference Between Actual and Counterfactual for Wheat (cf Table 3 in CRS)

	2006-07	2007-08	2008-09	2009-10	2010-11	Average
No Inventory-Demand Shocks						
Inventory	-0.05	0.26	0.17	0.27	0.59	0.25
Fut. Price	-0.02	0.12	0.04	0.07	0.19	0.08
Conv. Yield	0.01	-0.05	0.00	-0.01	-0.05	-0.02
Cash Price	-0.01	0.08	0.04	0.06	0.14	0.06
No Inventory-Demand or -Supply Shocks						
Inventory	-0.06	-0.28	0.21	0.60	0.34	0.16
Fut. Price	-0.01	0.52	0.07	-0.12	0.39	0.17
Conv. Yield	0.01	0.04	-0.04	-0.07	0.02	-0.01
Cash Price	0.00	0.56	0.03	-0.19	0.41	0.16
No Inventory-Demand Shocks						
Inventory-Supply Shocks from Production Surprises Only						
Inventory	-0.04	-0.22	0.18	0.52	0.27	0.14
Fut. Price	-0.03	0.48	0.09	-0.06	0.45	0.18
Conv. Yield	0.01	0.03	-0.03	-0.06	0.02	-0.01
Cash Price	-0.03	0.51	0.05	-0.12	0.48	0.18
No Inventory-Demand Shocks (80% confidence band)						
Inventory-Supply Shocks from Production Surprises Only						
Inventory	-0.15 0.09	-0.46 -0.04	-0.18 0.44	0.11 0.83	-0.16 0.67	-0.15 0.39
Fut. Price	-0.11 0.05	0.36 0.64	-0.06 0.34	-0.18 0.19	0.32 0.71	0.08 0.38
Conv. Yield	-0.03 0.04	-0.02 0.08	-0.11 0.02	-0.13 -0.01	-0.05 0.06	-0.06 0.03
Cash Price	-0.10 0.06	0.39 0.67	-0.09 0.29	-0.24 0.12	0.34 0.71	0.07 0.36
Identified Set						
No Inventory-Demand Shocks						
Inventory-Supply Shocks from Production Surprises Only						
Inventory	-0.02 0.02	-0.19 -0.13	0.14 0.16	0.30 0.43	-0.06 0.15	0.05 0.10
Fut. Price	-0.04 -0.04	0.46 0.46	0.10 0.11	-0.03 -0.01	0.50 0.53	0.20 0.21
Conv. Yield	0.00 0.00	0.02 0.02	-0.03 -0.02	-0.04 -0.02	0.03 0.04	0.00 0.00
Cash Price	-0.05 -0.04	0.48 0.49	0.07 0.09	-0.07 -0.02	0.53 0.58	0.20 0.22
Identified Set (>80% confidence band)						
No Inventory-Demand Shocks						
Inventory-Supply Shocks from Production Surprises Only						
Inventory	-0.14 0.14	-0.44 0.06	-0.23 0.41	-0.11 0.75	-0.48 0.55	-0.24 0.36
Fut. Price	-0.12 0.04	0.35 0.63	-0.05 0.36	-0.14 0.24	0.36 0.79	0.09 0.41
Conv. Yield	-0.04 0.04	-0.03 0.07	-0.10 0.03	-0.11 0.02	-0.04 0.08	-0.06 0.05
Cash Price	-0.12 0.05	0.37 0.65	-0.07 0.33	-0.19 0.21	0.39 0.79	0.09 0.40
Production Surprises (MMT)						
Actual Prod.	49.2	55.8	68.4	60.1	58.9	
May Forecast	51.0	59.2	65.1	55.1	55.6	
Surprise	-1.8	-3.3	3.3	5.0	3.3	

Note: Here we define the log cash price as log futures plus convenience yield. Table entries are results from the BAU calculations described in the text. Surprise terms divided by 18.7 MMT, which is average wheat inventory from 1996-2005. Because the identifying assumptions differ slightly, there is no requirement that the point identified parameters lie in the identified set.