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COMMODITY PRICE VOLATILITY IN THE BIOFUEL ERA: AN EXAMINATION OF THE LINKAGE BETWEEN ENERGY AND AGRICULTURAL MARKETS

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ABSTRACT

Agricultural and energy commodity prices have traditionally exhibited relatively low correlation. However, recent increases in biofuel production have altered the agriculture-energy relationship in a fundamental way. This increase has drawn on corn previously sold to other uses, as well as acreage devoted to other crops. The US RFS envisions a further boost of ethanol production to 15 billion gallons per year, which might be expected to further strengthen the linkages. We estimate that, in the presence of a binding RFS, the inherent volatility in the US coarse grains market will rise by about one-quarter. And the volatility of the US coarse grains price to supply side shocks in that market will rise by nearly one-half.

Under a high oil price scenario, rather than the RFS binding, the binding constraint is likely to be the blend wall. With a binding blend wall, we see similar, although somewhat smaller, increases in market volatility. If both the RFS and the blend wall are on the verge of being binding, then our results suggest that US coarse grains price volatility in response to corn supply shocks would be 57% higher than in the non-binding case, and world price volatility would be boosted by 25%.

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Commodity Price Volatility in the Biofuel Era: An Examination of the Linkage between Energy and Agricultural Markets

Introduction

US policy-makers have responded to increased public interest in reducing greenhouse gas (GHG) emissions and lessening dependence on foreign supplies of energy with a Renewable Fuels Standard (RFS) that imposes aggressive mandates on biofuel use in domestic refining. These mandates are in addition to the longstanding price policies (blending subsidies and import tariffs) used to promote the domestic ethanol industry's growth. Recently, a number of authors have begun to explore the linkages between energy and agricultural markets in light of these new policies (McPhail and Babock; Hochman, Sexton, and Zilberman; Gohin and Chantret; Tyner). It is clear from this work that we are entering a new era in which energy prices will play a more important role in driving agricultural commodity prices. However, based on experience during the past year, it is also clear that the coordination between energy and agricultural markets is fundamentally different at high oil prices vs. low oil prices, as well as in the presence of binding policy regimes.

Figure 1 illustrates how the linkage between energy and corn prices has varied over the 2001-2009 period. With oil prices below $75/barrel from January 2001 to August 2007, the correlation between monthly oil and corn prices was just 0.32. During much of this period, the share of corn production going to ethanol was still modest and ethanol capacity was still being constructed. Also, considerable excess profits appear to have been available to the industry over this period (Figure 2) – a phenomenon which loosened any potential link between ethanol prices, on the one hand and corn prices on the other. Indeed, Tyner (2009a) reports a -0.08 correlation between ethanol and corn prices in the period, 1988-2005. The year 2006 was a key turning point in the ethanol market, as this was when MTBE was banned as an additive and ethanol took over the entire market for oxygenator/octane enhancers in gasoline. In this use, the demand for ethanol was not very price-responsive and ethanol was priced at a premium when converted to an energy equivalent basis.

When oil prices reached and remained above $75/barrel from September 2007 to October 2008, the correlation between crude oil and corn became much stronger (0.92, see Figure 1 again), with per bushel corn prices remaining consistently at about 5% of crude oil prices/barrel. In this price range, the 2008 RFS appeared to be non-binding. However, as oil prices subsequently fell, many ethanol plants were moth-balled and the RFS became binding at year's end in 2008. That is to say: without this mandate, even less ethanol would have been produced in December of that year. Markets moved into a different price regime with the difference being made up in the value of the renewable fuel certificates required by blenders under the RFS.

While the RFS became temporarily non-binding with the onset of a new year in 2009, a new phenomenon began to emerge, namely the presence of a blend wall (Tyner, 2009b). With refineries unable to blend more than 10% ethanol into gasoline for normal consumption at that time, an excess supply of ethanol began to emerge in many regional markets. (Due to infrastructure limitations and state regulations[1] there is not a single

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[1] See ASTM-D4814

national market for ethanol). This led to a weakening of the link[2] between ethanol and oil prices, with the crude oil price continuing to fall, while corn prices, and hence ethanol prices, remained at levels that no longer permit ethanol to compete with petroleum on an energy basis; therefore, the monthly corn-petroleum price correlation in the final period reported in Figure 1 is much weaker (0.56).

In this paper, we develop a framework specifically designed for analyzing the linkages between energy and agricultural markets under different policy regimes.[3] We employ a combination of theoretical analysis, econometrics and stochastic simulation. Specifically, we are interested in examining how energy price volatility has been transmitted to commodity prices, and how changes in energy policy regimes affect the inherent volatility of agricultural commodity prices in response to traditional supply-side shocks. We find that biofuels have played an important role in facilitating increased integration between energy and agricultural markets. In the absence of a binding RFS, and assuming that the blend wall is relaxed by expanding the maximum permissible ethanol content in petroleum as has recently been the case, we find that, by 2015, the contribution of energy price volatility to year-on-year corn price variation will be much greater – amounting to nearly two-thirds of the crop supply-induced volatility. However, if the RFS is binding in 2015, then the role of energy price volatility in crop price volatility is diminished. Meanwhile, the sensitivity of crop prices to traditional supply-

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[2] An output-based link still exists under the blend wall since changes in the liquid fuel price affect the demand for biofuels by altering the consumption of liquid fuels. However, this now works in the opposite direction, as lower oil prices boost fuel consumption and hence ethanol demand.

[3] We ignore the non-market impacts of biofuels, which are important and have commanded much of the public's attention – particularly since the publication of Searchinger et al. (2008). Carbone and Smith (2008) point out how the presence of such considerations can introduce interactions which alter the market and welfare impacts of environmental policies.

side shocks is exacerbated due to the price inelastic nature of RFS demands. Indeed, the presence of a totally inelastic demand for corn in ethanol – stemming from the combination of a blend wall and a RFS both set in the range of 15 billion gallons/year -- would boost the sensitivity of corn prices to supply side shocks by more than 50%.

2. Literature Review

Energy, and energy intensive inputs play a large role in the production of agricultural products. Gellins and Parmenter (2004) estimate that energy accounts for 70-80% of the total costs used to manufacture fertilizers, which in turn represent a large component of corn production costs. Additional linkages come in the form of transportation of inputs and the final output, as well as the use of diesel or gasoline on-farm. Overall, USDA/ERS *Cost of Production* estimates indicate that energy inputs accounted for almost 30% of the total cost of corn production for the US in 2008.[4]

Another important linkage to energy markets is on the output side, as agricultural commodities are increasingly being used as feedstocks for liquid biofuels. Hertel, Tyner and Birur (2010) estimate that higher oil prices accounted for about two-thirds of the growth in US ethanol output over the 2001-2006 period. The remainder of this growth is estimated to have been driven by the replacement of the banned gasoline additive, MTBE, with ethanol in petroleum refining. In the EU, those authors estimate that biodiesel growth over the same period was more heavily influenced by subsidies. Nonetheless, those authors estimate that oil price increases accounted for about two-fifths of the expansion in EU biofuel production over the 2001-2006 period.

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[4] Comparing the USDA numbers across time regimes further strengthens our argument that the link between energy and agricultural commodities has increased over time. From 1996-2000 the average share of energy inputs (fertilizer and fuel, lube, and electricity) in total corn producer costs was 19.6%. From 2001-2004, this average share was 20.9%. But for 2007-2008 the share increased to 31.5%.

These growing linkages between energy and agricultural commodities have received increasing attention by researchers. Tyner (2009) notes that, since 2006, the ethanol market has established a link between crude oil and corn prices that did not exist historically. He finds that the correlation between annual crude oil and corn prices was negative (-0.26) from 1988-2005; in contrast, it reached a value of 0.80 during the 2006-2008. And, as Figure 1 shows, the correlation from September 2007-October 2008 was 0.92.

Du et al. (2009) investigate the spillover of crude oil price volatility to agricultural markets (specifically corn and wheat). They find that the spillover effects are not statistically significant from zero over the period from November 1998-October 2006. However, when they look at the period, October 2006-January 2009, the results indicate significant volatility spillover from the crude oil market to the corn market.

In a pair of papers focusing on the co-integration of prices for oil, ethanol and feedstocks, Serra, Zilberman and co-authors study the US (Serra et al., 2010a) and Brazilian (Serra et al, 2010b) ethanol markets. In the case of the US, they find the existence of a long term equilibrium relationship between these prices, with ethanol deviating from this equilibrium in the short term (they work with daily data from 2005 to 2007 in the case of the US, and weekly data in the case of Brazil). For the US the authors find the prices of oil, ethanol and corn to be positively correlated as might be expected, although they also find evidence of a structural break in this relationship in 2006 when the competing fuel oxygenator (MTBE) was banned and ethanol demand surged to fill this need. The authors estimate that a 10% perturbation in corn prices boosts ethanol prices by 15% -- a somewhat peculiar finding, given that corn represents only a portion of total ethanol costs.[5] From the other side, they find that a 10% rise in the price of oil leads to a 10% rise in ethanol, as one might expect of products that are perfect substitutes in use (perhaps an overly strong assumption in this case). In terms of temporal response time, they find that the response to corn prices is much quicker (1.25 months to full impact) than for an oil price shock (4.25 months).

In the Serra et al. (2010b) study of Brazil, the relevant feedstock is sugar cane. This presents a rather different commodity relationship since many of the sugarcane refining facilities can produce either ethanol or refined sugar, the latter which sells into the food market, not the energy market. Brazil also has a much more mature ethanol market. Ethanol production and use has been actively promoted by the government since the 1973 oil crisis and it now dominates petroleum in the domestic transportation market, with more than 70% of new car sales comprising flex-fuel vehicles accommodating either a 25%/75% ethanol/gasoline blend or 100% ethanol-based fuel. Serra et al. (2010b) build on the long-run price parity relationships between ethanol and oil, on the one hand (substitution in use), and ethanol and refined sugar on the other (substitution in production). They find that sugar and oil prices are exogenously determined and focus their attention on the response of ethanol prices to changes in these two exogenous drivers. The authors conclude that ethanol prices respond relatively quickly to sugar price changes, but more slowly to oil prices. A shift in either of these prices has a very short

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[5] In an industry characterized by zero pure profits, a cost share-weighted sum of input price changes must equal the percentage change in output price. With corn comprising less than full costs, then its price should change at a rate less than the output price, not more than the output price as reported in this study. For an industry starting in equilibrium to remain in equilibrium after corn prices rise by 10% and ethanol prices rise by 15%, returns to other inputs must also rise – likely by a very significant amount. Yet recent evidence suggests that higher corn prices reduce returns to capital in the US ethanol industry. So this is a puzzling result.

run impact on ethanol price volatility as well. Within one year, most of the adjustment to long run equilibrium in both markets has occurred. However, it takes nearly two years for the full effect of an oil price shock to be reflected in ethanol prices. So overall, these commodity markets are not as quick to regain long run equilibrium as those in the US, based on the results in these two studies. The authors do not find evidence of ethanol prices or oil prices affecting long run sugar prices over the period of their analysis, which spans the period: July 2000-February 2008.

Using similar time-series econometric techniques, Ubilava and Holt (2010) investigate a different, but related hypothesis regarding energy and feedstock prices in the US. They test the hypothesis that including energy prices in a time series model of corn prices should improve the latter's ability to forecast corn prices. Recognizing that this relationship might well be regime dependent (e.g., a closer linkage at high oil prices), they allow for such non-linear responses. However, their findings, using weekly averages of daily futures data for the US over the period October 2006 – June 2009, do not support these hypotheses, i.e., the inclusion of energy prices in the time series model does not improve its forecast accuracy. While they are asking a different question (and using weekly instead of daily data), this finding appears to stand at odds with the findings of Serra et al. (2010a) and suggests the need for replication and further testing of these models.

Based on this evidence it appears that, where it exists, the close link between crude oil prices and corn prices in the US is a relatively recent phenomenon; hence, econometric investigations of price transmission suffer from insufficient historical time series. For this reason, stochastic simulation has been an important vehicle to examine this topic in the US. McPhail and Babcock (2008) developed a partial equilibrium model to simulate the outcomes for the 2008/2009 corn market based on stochastic shocks to planted acreage, corn yield, export demand, gasoline prices, and the ethanol industry capacity. They estimate that gasoline price volatility and corn price volatility are positively related; and, for example, gasoline price volatility of 25% standard deviation (i.e., if prices are normally distributed, 68% of the time the gasoline price will be within ± 25% of the mean gasoline price) would lead to volatility in the corn price of 17.5% standard deviation.

Thompson et al. (2009) also utilize a stochastic framework (based on the FAPRI model) to examine how shocks to the crude oil (and corn) markets can affect ethanol price and use. They note that the RFS introduces a discontinuity between crude oil and ethanol prices. As a consequence, they find that the implied elasticity of a change in oil price on corn price is 0.31 (i.e., a 1% increase in the price of oil leads to a 0.31% increase in the corn price) with no RFS, and 0.17 with the RFS.[6] In subsequent work, Meyer and Thompson (2010) provide a more comprehensive analysis of the impact of biofuels and biofuel policies on corn price volatility using the FAPRI baseline. They find (perhaps not surprisingly) that the presence of tariffs and credits does not alter corn price volatility significantly. However, the introduction of a mandate, in the form of the US Energy Independence and Security Act, does cause some rise in volatility, although they do not provide information about how often the mandate is binding in their stochastic simulations.

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[6] These figures appear to be quite different from those offered by Serra et al. (2010a) for the US which appear to suggest a tighter relationship between oil and ethanol, and between corn and ethanol. However, those authors do not offer a comparable number in their paper.

A final paper in this line of partial equilibrium, stochastic simulation analyses of corn ethanol policies and corn prices is that of Gohin and Treguet (2010) who find that biofuels policies destabilize corn prices by reducing the frequency with which farm policy instruments are binding. These authors also introduce producer risk aversion into their model. Inclusion of down-side risk aversion dampens the supply response of producers to the biofuel policy. The presence of downside risk aversion also serves to contribute to additional welfare gains from biofuels policies, as producers are less exposed to low-end prices in the presence of these policies.

This review of the literature suggests the potential for some interesting hypotheses about potential linkages between agricultural and energy markets. The purpose of the next section of the paper is to develop an analytical framework within which these can be clearly stated as a set of formal propositions.

3. Analytical Framework

Consider an ethanol industry producing total output (Q_E) and selling it into two domestic market segments: in the first market, ethanol is used as a gasoline additive (QA_E), in strict proportion to total gasoline production.[7] As previously discussed, legal developments in the additive market (the banning of more economical MTBE as an oxygenator/octane enhancer) were an important component of the US ethanol boom between 2001 and 2006. The second market segment is the market for ethanol as a price-sensitive energy substitute (QP_E). In contrast to the additive market, the demand in this market depends importantly on the relative prices of ethanol and petroleum. For ease of

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[7] This may also be viewed as the "involuntary" demand for ethanol, in the words of Meyer and Thompson (2010). Those authors also include in this category additional state-level regulations such as the 10% ethanol blending requirement in the State of Minnesota.

exposition, and to be consistent with the general equilibrium specification introduced later on, we will model the additive demand as a derived demand by the petroleum refinery sector, and the energy substitution as being undertaken by consumers of liquid fuel. By assigning two different agents in the economy to these two functions, we can clearly specify the market shares governed by the two different types of behavior.[8]

Market clearing for ethanol, in the absence of exports, may then be written as:

$$Q_E = QA_E + QP_E \tag{1}$$

or, in percentage change form, where lower case denotes the percentage change in the upper case variable:

$$q_E = (1-\alpha)qa_E + \alpha qp_E \tag{2}$$

We denote the share of total ethanol output (Q_E) going to the price sensitive side of the market with $\alpha = QP_E / Q_E$.

Now we formally characterize the behavior of each source of demand for ethanol as follows (again, lower case variables denote percentage changes in their upper case counterparts):

$$qa_E = q_F \tag{3}$$

where q_F is the percentage change in the total production of liquid fuel, for which the additive/oxygenator is demanded in fixed proportions. The price sensitive portion of ethanol demand can be parsimoniously parameterized as follows:

$$qp_E = qp_F - \sigma(p_E - p_F) \tag{4}$$

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[8] This modeling of the two different ethanol uses gives rise to the ‘kinked-demand’ curve referred to by some authors (e.g., McPhail and Babcock, 2008).

Where qp_F is the percentage change in total liquid fuel consumption by the price sensitive portion of the market (i.e. households), and σ is the constant elasticity of substitution amongst liquid fuel sources consumed by households. The price ratio P_E / P_F refers to the price of ethanol, relative to a composite price index of all liquid fuel products consumed by the household. The percentage change in this ratio is given by the difference in the percentage changes in the two prices: $(p_E - p_F)$. When pre-multiplied by σ, this determines the price-sensitive component of households' change in demand for ethanol. Substituting (3) and (4) into (2), we obtain a revised expression for ethanol market clearing:

$$q_E = (1-\alpha)(qa_E) + \alpha[qp_F - \sigma(p_E - p_F)] \tag{5}$$

On the supply side, we assume constant returns to scale in ethanol production, which, along with entry/exit (a very common phenomenon in the ethanol industry since late 2007 – indeed today plants shut down one month and start up the next), gives zero pure profits:

$$p_E = \sum_j \theta_{jE} p_{jE} \tag{6}$$

Where p_E is the percentage change in the producer price for ethanol, p_{jE} is the percentage change in price of input j, used in ethanol production, and θ_{jE} is the share of that input in total ethanol costs (see Figure 2 for evidence of the validity of (6) since 2007). Assuming non-corn inputs supplied to the ethanol sector in this partial equilibrium model (e.g., labor and capital) are in perfectly elastic supply, and abstracting from direct energy use in ethanol production (both assumptions will be relaxed in the numerical general equilibrium model below) we have $p_{jE} = 0, \ \forall j \neq C$, and we can solve (6) for the corn price in terms of ethanol price changes:

$$p_{CE} = \theta_{CE}^{-1} p_E \, . \tag{7}$$

Assuming that corn is used in fixed proportion to ethanol output (i.e. Q_{CE} / Q_E is fixed), we can complete the supply–side specification for the ethanol market with the following equations governing the derived demand for, and supply of, corn in ethanol:

$$q_{CE} = q_E \tag{8}$$

$$q_{CE} = \nu_{CE} p_{CE} \tag{9}$$

where ν_{EC} is the *net* supply elasticity of corn to the ethanol sector, i.e., it is equal to the supply elasticity of corn, net of the price responsiveness in other demands for corn (outside of ethanol). This will be developed in more detail momentarily when we turn to equilibrium in the corn market. Substituting (9) into (8) and then using (7) to eliminate the corn price, we obtain an equation for the *market supply of ethanol*:

$$q_E = \nu_{CE} \theta_{CE}^{-1} p_E \tag{10}$$

Now turn to the corn market, where there are two sources of demand for corn output (Q_C): the ethanol industry, which buys Q_{CE}, and all other uses of corn, Q_{CO}. Letting β denote the share of total corn sales to ethanol, market clearing in the corn market may thus be written as:

$$q_C = \beta q_{CE} + (1\text{-}\beta) q_{CO} \tag{11}$$

We characterize non-ethanol corn demands as consisting of two parts: a price sensitive portion governed by a simple, constant elasticity of corn demand, η_{CD}, as well as a random demand shock (e.g., stemming from a shock to GDP in the home or foreign markets), Δ_{CD}. Ethanol demand for corn has already been specified in (8). We will shortly solve for q_{CE}, so we leave that in the equation, giving us the following market clearing condition for corn:

$$q_C = \beta q_{CE} + (1\text{-}\beta)(\eta_{CD} p_C + \Delta_{CD}) \tag{12}$$

As with demand, corn supply is specified via a price responsive portion, governed by the constant elasticity of supply, η_{CS}, and a random supply shock (e.g., driven by weather volatility), Δ_{CS}, yielding:

$$q_C = \eta_{CS} p_C + \Delta_{CS} \tag{13}$$

At this point, we can derive an expression for the net corn supply to ethanol production by solving (12) for q_{CE} and using (13) to eliminate corn supply (q_C). This yields the following expression for net corn supply to the ethanol industry:

$$q_{CE} = \{[\eta_{CS}\text{-}(1\text{-}\beta)\eta_{CD}]/\beta\} p_C + (\Delta_{CS}\text{-}(1\text{-}\beta)\Delta_{CD})/\beta \tag{14}$$

The term in brackets {.} is ν_{CE}, the *net* supply elasticity of corn to the ethanol sector.[9] With $\beta < 1$ and $\eta_{CD} < 0$, this net supply elasticity is larger than the conventional corn supply elasticity, with the difference between the two diminishing as the share of corn sold to ethanol grows ($\beta \to 1$) and the price responsiveness of other corn demands falls ($\eta_{CD} \to 0$).

The second term in (14) translates random shocks to corn supply and other corn demands into random shocks to net corn supply to ethanol. The larger the shocks, the

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[9] This expression closely resembles the earlier work of de Gorter and Just (2008).

more volatile are the shocks to corn supply and demand (which we will assume to be independently distributed in the empirical section below) and the smaller the share of ethanol demand in total corn use. We denote the total effect of this random component (the second term in (14)) by the term Δ_{CE} which we term the random shock to the net supply of corn to the ethanol industry.

We can now solve this simple model for equilibrium in the corn ethanol market. To do so, we make a number of additional assumptions. Firstly, we assume that growth in the household portion of the liquid fuel market (qp_F) is equal to growth in total liquid fuel use (q_F), and that this aggregate liquid fuel demand may be characterized via a constant elasticity of demand for liquid fuels, η_{FD}. This permits us to write the aggregate demand for ethanol as follows:

$$q_E = \eta_{FD} p_F - \alpha\sigma(p_E - p_F) \tag{15}$$

For purposes of this simple, partial equilibrium, analytical exercise, we will assume that the share of ethanol in aggregate liquid fuel use is small, so that we may ignore the impact of p_E on p_F. In so doing, we will consider the liquid fuels price to be synonymous with the price of petroleum. Thus a one percent shock to the price of ethanol will reduce total ethanol demand by $\alpha\sigma$. Conversely, a one percent exogenous shock to the price of petroleum, has two separate effects on the demand for ethanol, one negative (the expansion effect) and one positive (the substitution effect): $\eta_{FD} + \alpha\sigma$. Provided the share of total sales to the price-responsive portion of the market (α) is large enough, and assuming ethanol is a reasonably good substitute for petroleum, then the second (positive) term dominates and we expect the rise in petroleum prices to lead to a rise in the demand for ethanol. However, if for some reason the second term is eliminated – for example due to ethanol demand encountering a blend wall, as described by Tyner (2010) – then this relationship may be reversed, i.e. a rise in petroleum prices will reduce the aggregate demand for liquid fuels, and, in so doing, it will reduce the demand for ethanol.

We solve the model by equating ethanol supply (14) to ethanol demand (15), noting that corn demand in ethanol changes proportionately with ethanol production (8), and using (7) to translate the change in corn price into a change in ethanol price.

$$q_E = \nu_{CE}\theta_{CE}^{-1} p_E + \Delta_{CE} = \eta_{FD} p_F - \alpha\sigma(p_E - p_F) \tag{16}$$

Equation (16) may be solved for the price of ethanol as a function of exogenous shocks to the corn market and to the liquid fuels market:

$$(\nu_{CE}\theta_{CE}^{-1} + \alpha\sigma) p_E = (\eta_{FD} + \alpha\sigma) p_F - \Delta_{CE} \tag{17}$$

Giving rise to:

$$p_E = [(\eta_{FD} + \alpha\sigma) p_F - \Delta_{CE}] / (\nu_{CE}\theta_{CE}^{-1} + \alpha\sigma) \tag{18}$$

This equilibrium outcome may be translated back into a change in corn prices, via (7):

$$p_C = [(\eta_{FD} + \alpha\sigma) p_F - \Delta_{CE}] / (\nu_{EC} + \theta_{EC}\alpha\sigma) \tag{19}$$

It is now clear that a random shock to the non-ethanol, corn market which in turn perturbs the net supply of corn to ethanol (Δ_{CE}) will result in a larger change in corn price, the more inelastic are corn supply and demand (as reflected by the ν_{CE} term in the denominator of (19)) and the smaller the elasticity of substitution between ethanol and petroleum (σ), the smaller the share of ethanol going to the price responsive portion of the fuel market (α), and the smaller the cost share of corn in ethanol production (θ_{CE}).

However, the role of the sales share of corn going to ethanol (β), is ambiguous and requires further analysis.

Consider first, the impact only of a random shock to corn supply. Substitute into (19) the following relationships:

$$v_{CE} = \{[\eta_{CS}\text{-}(1\text{-}\beta)\eta_{CD}]/\beta\}\text{, and } \Delta_{CE} = (\Delta_{CS}\text{-}(1\text{-}\beta)\Delta_{CD})/\beta\,. \tag{20}$$

And ignore the demand-side shock to obtain:

$$p_C = [-\Delta_{CS}/\beta]/(\{[\eta_{CS}\text{-}(1\text{-}\beta)\eta_{CD}]/\beta\} + \theta_{EC}\alpha\sigma) \tag{21}$$

Multiplying top and bottom by β and rearranging the denominator, we get:

$$p_C = [-\Delta_{CS}]/([\eta_{CS}\text{-}\eta_{CD}] + \beta[\theta_{EC}\alpha\sigma + \eta_{CD}]) \tag{22}$$

Now, it is clear that, provided the derived demand elasticity for corn in ethanol use exceeds that in other uses, i.e., $\theta_{EC}\alpha\sigma > -\eta_{CD}$, a rise in the share of corn sales to ethanol will dampen the volatility of corn prices in response to a corn supply shock. Of course, if something were to happen in the fuel market, for example, ethanol use hits the blend wall, then the potential for substituting ethanol for petroleum would be eliminated and the opposite result will apply, namely, an increased reliance of corn producers on ethanol markets will actually destabilize corn market responses to corn supply shocks. As we will see below, this is a very important result.

Similarly in the case of a corn demand shock, substitution into (19) and reorganization yields the following expression:

$$p_C = [(1\text{-}\beta)\Delta_{CD}]/([\eta_{CS}\text{-}\eta_{CD}] + \beta[\theta_{EC}\alpha\sigma + \eta_{CD}]) \tag{23}$$

The presence of $(1\text{-}\beta)$ in the numerator means that higher values of β reduce the size of the numerator. Provided the derived demand for corn by ethanol is more price responsive than non-ethanol demand, such that higher values of β increase the denominator in (23), we can say unambiguously that increased ethanol sales to corn results in more corn price stability in response to a given non-ethanol demand shock. However, when the derived demand for corn by ethanol is less price responsive than non-ethanol demand, the outcome is ambiguous.

Finally, consider the impact only of a random shock to fuel prices. Proceeding as above we obtain the following expression:

$$p_C = [(\eta_{FD} + \alpha\sigma) p_F] / [(\eta_{CS} - \eta_{CD}) / \beta + (\theta_{EC}\alpha\sigma + \eta_{CD})] \tag{24}$$

Note that now the impact of higher values of β is unambiguous – resulting in smaller values for the denominator, and therefore, more volatile corn prices in response to fuel price shocks. This makes sense, since a higher share of corn sold to ethanol boosts the importance of the liquid fuels market for corn producers. More generally, an increase in global fuel prices (p_F) will boost corn prices, in all but extreme cases wherein the sales share-weighted elasticity of substitution between ethanol and petroleum in price sensitive uses ($\alpha\sigma > 0$) is sufficiently dominated by the price elasticity of aggregate demand for liquid fuels ($\eta_{FD} < 0$). (Given the diminishing share of the additive market and the relatively inelastic demand for liquid fuels for transportation, this seems unlikely in the current economic environment.) The magnitude of this corn price change will be larger the more inelastic are corn supply and demand (as reflected in the denominator term ν_{EC}), the larger the share of corn going to ethanol (β), and the smaller the cost share of corn in ethanol production (θ_{CE})

We are now able to state several important propositions which form the basis for our empirical analysis below:

Proposition 1: A random shock to the corn market – either to supply (Δ_{CS}) or to demand (Δ_{CD}) -- will result in a larger change in corn price, the more inelastic are corn supply and demand (as reflected in the numerator of ν_{CE}), the smaller the elasticity of substitution between ethanol and petroleum ethanol (σ), the smaller the share of ethanol going to the price responsive portion of the fuel market (α), and the smaller the cost share of corn in ethanol production (θ_{CE}). The impact of the share of corn going to ethanol (β) depends on the relative responsiveness of corn demand in ethanol and non-ethanol markets. If the ethanol market is more price responsive, then an increase in β dampens the corn price volatility in response to a corn demand or supply shock. However, if the ethanol market is less price responsive (e.g., due to the blend wall) then higher sales to ethanol serve to destabilize the corn price response to a random shock in the market for corn.

Proposition 2: An increase in global fuel prices (p_F) will boost corn prices, provided the sales share-weighted elasticity of substitution between ethanol and petroleum in price sensitive uses ($\alpha\sigma > 0$) is not dominated by the price elasticity of aggregate demand for liquid fuels ($\eta_{FD} < 0$). The magnitude of this corn price change will be larger the more inelastic are corn supply and demand (as reflected in the denominator term ν_{EC}), the larger the share of corn going to ethanol (β), and the smaller the cost share of corn in ethanol production (θ_{CE}).

With a bit more information, we can also shed light on two important special cases in which policy regimes are binding. When oil prices are low, such that the Renewable Fuels Standard (RFS) is binding, then the total sales of corn to the ethanol market are pre-determined ($q_{CE} = 0$) so that the only price responsive portion of corn demand is the non-ethanol component. In this case, the equilibrium change in corn price simplifies to the following:

$$p_C = -\Delta_{CE} / \nu_{CE} \tag{25}$$

Note that the price of liquid fuel does not appear in this expression at all. Since our PE model abstracts from the impact of fuel prices on production costs of corn and ethanol, the RFS wholly eliminates the transmission of fuel prices through to the corn market by fixing the demand for ethanol in liquid fuels. The second point to note is that the responsiveness of corn prices to random shocks in the corn market is now magnified by the absence of the substitution-related term, $\theta_{CE}\alpha\sigma$, in the denominator. This leads to the third proposition.

Proposition 3: The binding RFS eliminates the output demand-driven link between liquid fuel prices and corn prices. Furthermore, with a binding RFS, the responsiveness of corn prices to a random shock in corn supply or demand is magnified. The extent of this magnification (relative to the non-binding case) is larger, the larger the share of ethanol going to the price responsive portion of the market, the larger the elasticity of substitution between ethanol and petroleum, and the larger the cost share of corn in ethanol production.

The other important special case considered below is that of a binding Blend Wall (BW). In this case, there is *no scope for altering the mix* of ethanol in liquid fuels. Therefore the substitution effect in (15) drops out and the demand for ethanol simplifies to:

$$q_E = \eta_{FD} p_F \tag{26}$$

In this case, the equilibrium corn price expression simplifies to the following:

$$p_C = (\eta_{FD} p_F - \Delta_{CE}) / \nu_{CE} \tag{27}$$

Note that the price of liquid fuel has re-appeared in the numerator, but the coefficient pre-multiplying this price is now negative. This gives rise to the fourth, and final, proposition.

Proposition 4: The presence of a binding Blend Wall changes the qualitative relationship between liquid fuel prices and corn prices. Now, a fall in liquid fuel prices, which induces additional fuel consumption, will stimulate the demand for corn and hence boost corn prices. As with the binding RFS, the responsiveness of corn prices to a random shock in corn supply or demand is again magnified. The extent of this magnification (relative to the non-binding case) is larger, the larger the share of ethanol going to the price responsive portion of the market, the larger the elasticity of substitution between ethanol and petroleum, and the larger the cost share of corn in ethanol production.

This simple, partial equilibrium analysis of the linkages between liquid fuel and corn markets has been useful in sharpening our thinking about key underlying relationships. However, it is necessarily rather simplified. As noted above, we have ignored the role of energy input costs in corn and ethanol production – even though these are rather energy intensive sectors. We have also ignored the important role of biofuel by-products. Yet, sales of Dried Distillers Grains with Solubles (DDGS) account for about 16% of the industry's revenues and their sale competes directly with corn and other feedstuffs in the livestock industry (Taheripour et al., 2010). And we have failed to distinguish feed demands for corn from processed food demands. Finally, we have abstracted from international trade, which has become an increasingly important dimension of the corn, ethanol, DDGS and liquid fuel markets. For all these reasons, the empirical model introduced in the next section is more complex than that laid out above. Nonetheless, we will see that the fundamental insights offered by propositions 1 – 4 continue to be reflected in our empirical results.

4. Empirical Framework

Overview of the Approach: Given the characteristic high price volatility in energy and agricultural markets, the complex interrelationships between petroleum, ethanol, ethanol by-products and livestock feed use, and agricultural commodity markets, as well as the constraining agricultural resource base, and the prominence of food and fuel in household budgets and real income determination, the economy-wide approach of an applied general equilibrium (AGE) analysis can offer a useful analytical framework for this paper. The value of a global, AGE approach in analyzing the international trade and land use impacts of biofuel mandates has previously been demonstrated in the work of Banse et al. (2008), Gohin and Chantret (2010), and Keeney and Hertel (2009). The commodities in question are heavily traded and, by explicitly disaggregating the major producing and consuming regions of the world we are better able to characterize the fundamental sources of volatility in these markets.

From Jorgenson's (1984) emphasis on the importance of utilizing econometric work in parameter estimation, to more recent calls for rigorous historical model testing (Hertel, 1999; Kehoe, 2003; Grassini, 2004), it is clear that CGE models must be adequately tested against historical data to improve their performance and ensure reliability. The article by Valenzuela et al., (2007) showed how patterns in the deviations between CGE model predictions and observed economic outcomes can be used to identify the weak points of a model and guide development of improved specifications for the modeling of specific commodity markets in a CGE framework. More recent work by Beckman, Hertel, and Tyner (2011) has focused on the validity of the GTAP-E model for analysis of global energy markets.

Accordingly, we begin our work with a similar, historical validation exercise. In particular, we examine the model's ability to reproduce observed price volatility in global corn markets in the pre-biofuels era (up to 2001). For the sake of completeness, as well as to permit us to analyze their relative importance, we augment the supply-side shocks (as derived from Valenzuela et al., 2007) by adding volatility in energy markets (specifically oil) and in aggregate demand (as proxied by volatility in national GDPs) following

Beckman, Hertel, and Tyner (2011). With these historical distributions in hand, we are then in a position to explore the linkages between volatility in energy markets and volatility in agricultural markets.

Applied General Equilibrium Model: The impacts of biofuel mandates are far-reaching, affecting all sectors of the economy and trade, which creates potential market feedback effects. To capture these effects across production sectors and countries, we use the global AGE model, GTAP-BIO (Taheripour et al., 2007), which incorporates biofuels and biofuel co-products into the revised/validated GTAP-E model (Beckman, Hertel, and Tyner, 2011). GTAP-BIO has been used to analyze the global economic and environmental implications of biofuels in Hertel et al. (2008), Taheripour et al. (2008), Keeney and Hertel (2009), and Hertel, Tyner, and Birur (2010).

Experimental Design: The GTAP data base used here (v.6) is benchmarked to 2001; therefore we undertake a historical update experiment to 2008 following the approach utilized by Beckman, Hertel, and Tyner (2011). Those authors show that by shocking population, labor supply, capital, investment and productivity changes (see Table 2), along with the relevant energy price shocks, the resulting equilibrium offers a reasonable approximation to key features of the more recent economy.

This updating of the model also allows us the opportunity to test the model's ability to replicate the strengthened relationship between energy and agricultural prices. We do so by implementing the very same stochastic shocks used for the validation experiment in 2001, only now on our updated 2008 economy. As Figure 1 illustrated, the observed correlation between oil and corn prices strengthened considerably over the 2001-2008 time period (note that before 2001, the correlation between the two was negative); therefore, our hypothesis (and indeed our model performance check) is that the transmission of energy price volatility will be higher than the pre-2001 period. Updating the model also allows us the chance to explore some of the empirical dimensions of propositions 1-4 which emerged from the theoretical model.

All of this work sets the stage for an in-depth exploration of the role of biofuel policy regimes in governing the extent to which volatility in energy markets is transmitted to agricultural commodity markets and the extent to which increased sales of agricultural commodities to biofuels alters the sensitivity of these markets to agricultural supply-side shocks. For this part of the analysis, we focus on the year 2015, in which the RFS for US corn ethanol reaches its target of 15 billion gallons/year, and a blend wall could potentially be binding. In order to reach the target amount, we implement a quantity shock to the model which will increase US ethanol production to 15 billion gallons/year. We do not run a full update experiment, as we did for the 2001-2008 time period, since we do not know how the key exogenous variables will evolve over this future period.[10] We assume that the distributions of supply side shocks in agriculture and energy markets, as well as the inter-annual volatility in regional GDPs remain unchanged from their historical values; this has the virtue of allowing us to isolate the impact of the changing structure of the economy on corn price volatility.

Based on Proposition 4, we hypothesize that, at low oil prices, stochastic draws in the presence of a binding RFS will render corn markets more sensitive to agricultural supply-side shocks, since a substantial portion of the corn market (the mandated ethanol

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[10] Obviously we could use projections of key variables, but they would be uncertain, and we do not believe this would significantly alter our findings, which hinge primarily on the quantity and cost shares featured in equation (19).

use) will be insensitive to price, while at high corn prices, the opposite will be true, due to the highly elastic demand for ethanol as a substitute for corn. On the other hand, again, based on Proposition 4, we expect energy market volatility to have relatively little impact on corn markets at low oil prices.

At high oil prices there are two possibilities – in the first case, the RFS is non-binding and the blend wall is not a factor (i.e., it has recently been increased from 10% to 15% for recent model vehicles). In this case, we expect to see the influence of a larger share of corn going to ethanol (β), and also a larger share of ethanol going to the price responsive portion of the fuel market (α), translated into lesser sensitivity to random supply shocks emanating from the corn market (Proposition 1).

In the second case, high oil prices induce expansion of the ethanol industry to the point where the blend wall is binding so that Proposition 4 becomes relevant. In this case, the qualitative relationship between oil prices and corn prices is reversed; as with the binding RFS, the impact of random shocks to corn supply or demand will be magnified with a binding blend wall.

Before investigating these hypotheses empirically, we must first characterize the extent of volatility in agricultural and energy markets. In terms of the PE model developed above, we must estimate the parameters underlying the distributions of Δ_{CS}, Δ_{CD}, and p_F.

5. Characterizing Sources of Volatility in Energy and Agricultural Markets

The distributions of the stochastic shocks to corn production, corn demand and oil prices are assumed to be normally and independently distributed. Given the great many uses of corn in the global economy, we prefer to shock the underlying determinant of economy-wide demand, namely GDP, allowing these shocks to vary by model region. Of course GDP shocks also result in oil price changes, and, in a separate line of work, we have focused on the ability of this model to reproduce observed oil price volatility based on GDP shocks and oil supply shocks. However, in this paper, we prefer to perturb oil prices directly so that we may separately identify energy price shocks and more general shocks to the economy.

To characterize the systematic component in corn production, time-series models are fitted to National Agricultural Statistical Service (NASS) data on annual corn production (corn easily commands the largest share of coarse grains, the corresponding GTAP sector; hence the focus on corn) over the time period of 1981-2008[11]. For crude oil prices, we use Energy Information Administration (EIA) data on US average price and average import price (we take a simple average of the two series) over the same time periods. Here, we use the variation in regional Gross Domestic Product (GDP) to capture changes in aggregate demand in each of the markets.

The summary statistic of interest from the time-series regressions on both the supply and demand sides is the normalized standard deviation of the estimated residuals, reported in Table 3[12]. This result summarizes variability of the non-systematic aspect of annual production, prices and GDP in each region for the 1981-2008 time period (sectors and regions are defined in Appendices A1 and A2). This is calculated as $\sqrt{variance}$ (of estimated residuals) divided by the mean value of production (or prices, or GDP), and

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[11] We use the 1981-2008 time-period as the inputs for both the pre-2001 stochastic simulations and the 2001-2008, in order to not influence the comparison across base periods with the higher volatility of the 2001-2008 time period.

[12] Estimates for the time-series models are available upon request.

multiplied by 100%. Not surprisingly, from Table 3, we see that corn production and oil prices were much more volatile than GDP over the time period, with oil prices being somewhat more volatile than corn production. Note that we do not attempt to estimate region-specific variances for oil prices as we assume this to be a well-integrated market.

6. Results for 2001 and 2008

Pre-Biofuel Era: Our first task is to examine the performance of the model with respect to the 2001 base period. The first pair of columns in Table 4 reports the model-generated standard deviations in annual percentage change in coarse grains prices based on several alternative stochastic simulations. In the first column, we report the standard deviations in coarse grains prices when all three stochastic shocks from Table 3 are simultaneously implemented. Focusing on the US, the model with all three shocks predicts the standard deviation of annual percentage changes in corn prices to be 28.5, while the historical outcome (over the entire 1982-2008 period) revealed a standard deviation of just 20. So the model over-predicts volatility in corn markets. This is likely due to the fact that it treats producers and consumers as myopic agents who use only current information on planting and pricing to inform their production decisions. By incorporating forward looking behavior as well as stockholding, we would expect the model to produce less price variation. Introducing more elastic consumer demand would be one way of mimicking such effects and inducing the model to more closely follow historical price volatility.

The second column under the 2001 heading reports the impact on coarse grains price volatility of oil price shocks only. From these results, it is clear that the energy price shocks have little impact on corn markets in the pre-biofuel era. In the US, the amount of coarse grains price variation generated by oil price-only shocks is just a standard deviation of 1.1%, whereas the variation from the three sources is 28.5% (resulting in oil's share of the total equaling 0.04, as reported in parentheses in Table 4). This confirms the findings of Tyner (2009) who reports very little integration of crude oil and corn prices over the 1988-2005 period.

The third column in Table 4 reports the observed variation in coarse grains prices from volatility in corn production. This indicates that the majority of corn price variation in this historical period (0.96 of the total) was due to volatility in corn production.

Biofuel Era:

As discussed above, we update the data base to 2008 in order to provide a reasonably current representation of the global economy in the context of the biofuel era. We then redo the same stochastic simulation experiments as 2001 to explore the energy/agricultural commodity price transmission in the biofuel era. The middle set of columns in Table 4 present the results from this experiment.

The model estimates somewhat higher overall coarse grain price variation (standard deviation of 30.7%) in this case. Now, the ratio of the variation from energy price shocks to the total shocks is 0.32, versus the 0.04 for the 2001 data base. This is hardly surprising in light of expression (19) and Proposition 3. Referring to Table 1, which summarizes some of the key parameters/pieces of data from the three base years, we see that the shares of coarse grains going to ethanol production (β) rises, four-fold over this period. In addition, the share of ethanol going to the price sensitive side of the ethanol market (α) nearly doubles, and the net supply elasticity of corn to ethanol falls. Based on Proposition 3, all of these changes serve to boost the responsiveness of corn pries to liquid fuel prices. Meanwhile, the contribution of corn supply shocks to total volatility is somewhat reduced, as we would expect from the larger values for α , β and θ_{CE} , although the smaller net supply elasticity of corn to ethanol works in the opposite direction.

7. The Future of Energy-Agriculture Interactions in the Presence of Alternative Policies

Having completed our analysis of energy and agricultural commodity interactions in the current environment, we now turn to our analysis of US biofuel policies. US policy, given current technologies, mandates that 15 billion gallons of corn ethanol be produced by 2015 (this is known as the Renewable Fuel Standard (RFS[13])), up from roughly 7 billion gallons produced in 2008. We implement this mandate by increasing US ethanol production through an exogenous quantity increase, following Hertel, Tyner, and Birur (2010).

Mathematically, the RFS effectively provides a lower bound on ethanol production and may be represented via the following complementary slackness conditions, where S is the per unit subsidy required to induce additional use of ethanol by the price sensitive agents in our model, and QR is the ratio of observed ethanol use to the quota as specified under the RFS:

$S \geq 0 \perp (QR_{RFS} - 1) \geq 0$ which implies that either:

$S > 0, (QR_{RFS} - 1) = 0$ (RFS is binding) or:

$S = 0, (QR_{RFS} - 1) \geq 0$ (RFS is non-binding)

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[13] The RFS also mandates the production of advanced biofuels, which we do not consider here.

Since producers don't actually receive a subsidy for meeting the RFS, the additional cost of producing liquid fuels must be passed forward to consumers. We accomplish this by simultaneously taxing the combined liquid fuel product by the full amount of the subsidy.

The key point regarding the RFS is that it is asymmetric. Thus, when the RFS is just binding ($S \ = 0, (QR_{RFS} - 1) = 0$, any rise in the price of gasoline will increase ethanol production past the mandated amount, since ethanol is now better able to compete with gasoline on an energy basis. In this case, corn demand (and price) will be responsive to changes in the oil price. In contrast, a decrease in the price of gasoline does nothing to ethanol production (i.e., it stays at the 15 billion gallon mark) as this is the mandated amount; $S \ > 0$ ensures that the ethanol continues to be used at current levels. Of course, if the RFS is severely binding ($S \ >> 0, (QR_{RFS} - 1) = 0$), then oil prices will have to rise considerably before reaching the point where $S \ = 0$ and the fuel price begins to translate through to the corn price. Since it is very difficult to predict whether the RFS will be binding in 2015, and if so, how severely binding it will be, we adopt the simple assumption that the RFS is just barely binding in the initial equilibrium. Therefore any rise in oil prices will translate through to corn prices.

A blend wall works differently from the RFS; as pointed out by Tyner (2009), the blend wall is an effective constraint on demand[14]. Mathematically, the blend wall provides an upper bound on the ethanol intensity of liquid fuels and may be represented via the following complementary slackness conditions, where T is the per unit tax

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[14] The Energy Information Agency estimates U.S. gasoline consumption at approximately 135 billion gallons; therefore, if the entire amount was blended with ethanol, we would fall short of the 15 billion gallon mark. Several alternatives have been suggested such as improving E-85 demand; and increasing the blending regulation (this is currently being investigated by the Environmental Protection Agency) to 12-15%.

required to restrict additional use of ethanol, and QR is the ratio of observed ethanol intensity (Q_E / Q_F) to the blend wall.

$T \geq 0 \perp (1 - QR_{BW}) \geq 0$ which implies that either:

$T > 0, (1 - QR_{BW}) = 0$ (BW is binding) or:

$T = 0, (1 - QR_{BW}) \geq 0$ (BW is non-binding)

For illustrative purposes, consider the case in which the BW is just barely binding so that $T = 0, (1 - QR_{BW}) = 0$, but the RFS is not binding. Then if the price of gasoline were to rise, the ethanol intensity of liquid fuel use would not change, since it is up against the blend wall. Of course the overall level of ethanol production may well fall, as total liquid fuel consumption falls, thereby dragging down the maximum amount of ethanol which can be added. In this case, the tax adjusts to ensure the constraint remains binding. However, if the price of gasoline falls, the ethanol intensity of production will decline, thereby moving off this constraint such that the Blend Wall becomes non-binding.

As with the RFS, it is difficult to predict the extent to which the blend wall will be binding in 2015. However, given the strong political interest in maintaining ethanol production, at the time of the NBER conference (Spring, 2010) we viewed it as likely that the blend wall would be adjusted upward in the future in order to permit the industry to meet the RFS. At the time of our revision of this chapter, this has indeed been done by the US-EPA, with the blend rate for recent model vehicles now raised to 15%. It seems unlikely that E85 use will expand greatly in the US due to infrastructure limitations (the flex-fuel auto stock is limited and therefore the number of fuel stations offering E85 is also quite limited); therefore, it is reasonable to consider the case wherein the blend wall is adjusted such that it is just becoming binding at the 2015 RFS level.

Given the many different combinations of RFS and blend wall policy regimes, we investigate the importance of energy price shocks on agricultural commodity prices under four different scenarios:

1) *Base case*: the RFS is not binding under any combination of commodity market shocks and the blend wall is ignored. We expect that this base case will offer the largest scope for energy price shocks to influence agricultural commodity price volatility. Results from this case are reported in the last part of Table 4.
2) *RFS is just binding*, i.e., corn ethanol production is precisely 15 billion gallons in 2015. In this case, if oil prices rise, due to a random shock to the petroleum market, ethanol production will also rise, as this fuel is substituted for the higher priced petroleum. However, the effect of declining petroleum prices will not be translated back to the corn market, as the RFS will prevent a contraction of ethanol production. This has the effect of making corn demand more inelastic such that commodity price volatility is greater in the wake of the supply-side shocks. Results from this and the subsequent experiments are reported in Table 5.
3) *RFS is not binding*; however, *the blend wall is binding*. In this case, we assume that the strength of the overall economy as well as the relative prices of petroleum and corn in 2015 are such that ethanol production is well above the level specified by the RFS so that the random shocks introduced below never threaten to push production below the 15 billion gallon annual target. However, in this case the blend wall is very likely to be binding, and we specify the initial conditions in the

model such that $T = 0, (1 - QR_{BW}) = 0$, i.e. the blend wall is on the verge of binding. In this case, we expect the impact of an oil price rise on corn price volatility to be very modest, as it is not possible to increase the ethanol intensity of liquid fuels, so the only changes in ethanol use will be those emanating from changes in overall liquid fuel use.

4) *RFS and blend wall are both on the verge of binding*. This scenario could arise if the blend wall were continually adjusted upwards, just reaching the point at which the RFS is met. In this case we have: $T = 0, (1 - QR_{BW}) = 0$ and $S = 0, (QR_{RFS} - 1) = 0$.

Let us first consider the 2015 base case results presented in Table 4. These indicate that, relative to the 2008 data base, in the absence of any role for the RFS and Blend Wall (BW), energy price shocks contribute more to coarse grain price variation. Indeed, energy price volatility now contributes to a standard deviation of 15.6, which amounts to 0.53 of the total variation in corn prices (but still less than the independent variation induced by corn supply side shocks). This result is expected, as even more corn is going to ethanol production (Table 1), and there is double the amount of ethanol produced, compared to the 2008 data base. In addition, ethanol production is free to respond to both low and high oil price draws from the stochastic simulations, since the RFS and BW are non-binding. The contribution of corn supply-side volatility shocks to corn price variation is also lowest for this case.

For the second scenario we follow the same process as before to stimulate ethanol production to the RFS amount and we run the same stochastic simulations; however, as noted above, we assume that the RFS is initially just binding and we implement the requirement that US ethanol production can not fall below 15 billion gallons. Results for this scenario indicate (refer to Table 5) that that the share of energy price volatility to total corn price variation is cut in half from the base case (from 0.53 to 0.26). This is due to the fact that we truncate consumers' to response to low oil price draws by using less ethanol. Implementation of the RFS also leads to much higher variation in corn prices. In proposition 3, we demonstrated the cause of this, i.e., the RFS severs the consumer demand-driven link between liquid fuels price and corn prices in the presence of low oil prices. The absence of price responsiveness in this important sector translates into a magnification of the responsiveness of corn prices to random shocks to corn supplies and non-ethanol demand.

These results are similar to those from Yano, Blandford, and Surry (2010) who use Monte Carlo simulations of a PE model to show that the US ethanol mandate reduces the impact that variations in petroleum prices on corn prices (compared to a 'no-mandate' scenario), while the impacts from variations in corn supply on corn prices are increased.

For the third scenario, we allow the RFS to be non-binding, but we implement a blend wall, which itself is assumed to be just binding. The results from this case indicate that the share of energy price volatility in total corn price variation is even lower than when the RFS is just binding. This is substantiated by Tyner (2009) who notes that the blend wall effectively breaks the link between crude oil and corn prices, as ethanol cannot react to high oil prices; but at low oil prices the blend wall does little to reduce demand for ethanol.

The final scenario in Table 5 is the case wherein both the RFS and the BW are on the verge of binding. This largely eliminates the demand-side feedback from energy prices to the corn market, which is what we see in the results, with oil price volatility accounting for just 0.03 of the total variation in corn prices. In contrast, the price responsiveness of corn to supply side shocks is greatly increased. Indeed, when compared to the 2015 base case (no RFS, no BW), corn price volatility in the face of identical supply side shocks is 57% greater. If we look at the final row of Table 5, we see that global price volatility is much increased under this scenario, rising by about one-quarter. Clearly the presence of biofuel mandates and associated fuel blending limits have the potential to greatly destabilize agricultural commodity markets in the future.

In addition to price volatility, it is useful to consider the mean price change from the 2015 base. Table 6 reports mean changes in both ethanol production and corn prices in the US under different policy regimes. Due to the nature of the demand relationships in the model, production shortfalls generate larger price changes than do symmetric instances of excess production, and the mean corn price change under the base case is greater than zero. When the RFS and Blend Wall are both binding, ethanol production is unchanged and the mean change in corn price is even larger, at 12.2%. When only the RFS is binding, instances of high corn prices – potentially due to a production shortfall – are rewarded with persistent ethanol demand, due to the mandate. This has a tendency to boost mean ethanol production, as well as mean corn prices. On the other hand, when only the blend wall is binding, episodes of low corn prices – possibly due to a favorable draw from the coarse grains productivity distribution – no longer result in greater ethanol production, as the blend wall prevents further expansion. However, high corn prices do result in lower ethanol use, which is why the mean change in ethanol production is -21% under the BW scenario. This results in lower expected corn prices as well.

8. Discussion

The relationship between agricultural and energy commodity markets has strengthened significantly with the recent increase in biofuel production. Energy has always played an important role in agricultural production inputs; however, the combination of recent high energy prices with policies aimed at promoting energy security and renewable fuel use have stimulated the use of crop feedstocks in biofuel production. With a mandate to further increase biofuel production in the US, it is clear that the relationship amongst agricultural and energy commodities may grow even stronger.

Results from this work indicate that the era of rapid biofuel production strengthened the transmission of energy price volatility into agricultural commodity price variation. The additional mandated production has the potential to further strengthen this transmission. However, the outcome will depend critically on the policy regime in which ethanol markets find themselves. The presence of a Renewable Fuels Standard can hinder the ethanol's sectors ability to react to low oil prices, thereby destabilizing commodity markets. The presence of a liquid fuels blend wall causes a similar disconnection in the transmission of energy prices to agriculture – albeit at high oil prices, and therefore also serves to increase commodity price volatility.

Comparing all the scenarios considered here, the absence of all biofuel policies leads to the highest transmission of energy price volatility into commodity price variation and the lowest corn price volatility in response to traditional supply-side shocks. This is because consumers are able to respond to both high and low oil prices by changing their biofuel mix; and adjustment to corn supply shocks are absorbed by energy and non-energy markets alike. When we implement biofuels policy (either the RFS or a blend wall), the impacts from energy price volatility are smaller than the base case, while the impacts from corn supply volatility are magnified. In the most extreme case, wherein the blend wall is expanded to the point where the RFS is just barely binding, US coarse grains price volatility in response to corn supply shocks is 57% higher than in the non-binding case, and world price volatility is boosted by 25%. This underscores the point made by Irwin and Good (2010) who highlight the risk introduced by sizable sales of corn for ethanol production in the US, particularly in light of mandated minimum purchases. They suggest that this could lead to record price rises in the wake of an extreme weather event in the corn belt of the United States – something which has not been observed during recent years. This leads them to advocate introducing some type of safety valve for the biofuels program.

In summary, it seems likely we will experience a future in which agricultural price volatility – particularly for biofuel feedstocks – may rise. The extent of this volatility will depend critically on renewable energy policies. Indeed, in future these sources of uncertainty may become more important than traditional agricultural policies in many farm commodity markets.

References

Arndt, C. 1996. An Introduction to Systematic Sensitivity Analysis via Gaussian Quadrature. GTAP Technical Paper No. 2, Purdue University.

Beckman, J., Hertel, T. and W. Tyner. (2011). Validating Energy-Oriented CGE Models. *Energy Economics* (forthcoming).

Carbone, J.C. and V.K. Smith. 2008. "Evaluating Policy Interventions with General Equilibrium Externalities" *Journal of Public Economics,* 92(5-6):1254-1274.

de Gorter, H. and D. R. Just. ""Water" in the U.S. Ethanol Tax Credit and Mandate: Implications for Rectangular Deadweight Costs and the Corn-Oil Price Relationship." *Review of Agricultural Economics*, 30(3):397-410.

Du, X., Yu, C. and D. Hayes. 2009. "Speculation and Volatility Spillover in the Crude Oil and Agricultural Commodity Markets: A Bayesian Analysis." Presented at the Agricultural and Applied Economics Association, Milwaukee, Wisconsin.

Gellings, C. and K.E. Parmenter. 2004. "Energy Efficiency in Fertilizer Production and Use." in *Efficient Use and Conservation of Energy*, Eds. C.W. Gellings and K. Blok.

Gohin, A. and F. Chantret. 2010. "The Long-Run Impact of Energy Prices on World Agricultural Markets: The Role of Macro-Economic Linkages." *Energy Policy,* 38:333-339.

Gohin, A. and D. Treguer. 2010. "On the (De) Stabilization Effects of Biofuels: Relative Contributions of Policy Instruments and Market Forces"." *Journal of Agricultural and Resource Eocnomics,* 35(1):72-86.

Grassini, M. 2004. Rowing Along the Computable General Equilibrium Modeling Mainstream. Input-Output and General Equilibrium Data, Modeling, and Policy Analysis, Brussels.

Hertel, T.W., Tyner, W.E., and D.K. Birur, (2010). "Global Impacts of Biofuels." *Energy Journal*, 31(1):75-100.

Hertel, T., Golub, Jones, A., O'Hare, M., Plevin M., and D. Kammen (2010) "Global Land Use and Greenhouse Gas Emissions Impacts of US Maize Ethanol: Estimating Market-Mediated Responses." *BioScience* (forthcoming in March issue).

Hochman, G., Sexton, S. and D. Zilberman. 2008. "The Economics of Biofuel Policy and Biotechnology." *Journal of Agricultural & Food Industrial Organization*, Vol.6.

Irwin, S and D. Good (2010). “Alternative 2010 Corn Production Scenarios and Policy Implications.” Marketing and Outlook Brief, Department of Agricultural and Consumer Economics, University of Illinois, March 11.

Jorgenson, D. 1984. “Econometric Methods for Applied General Equilibrium Analysis.” Scarf, H.E. and J.B. Shoven (eds.), *Applied General Equilibrium Analysis.* New York, Cambridge University Press.

Keeney, R. and T. Hertel. 2009. “The Indirect Land Use Impacts of United States Biofuel Policies: The Importance of Acreage, Yield, and Bilateral Trade Response.” *American Journal of Agricultural Economics*, Vol. 91(4):895-909.

Kehoe, T. 2003. An Evaluation of the Performance of Applied General Equilibrium Models of the Impact of NAFTA. Federal Reserve Bank of Minneapolis, Research Department Staff Report 320.

McPhail, L. and B. Babcock. 2008. “Ethanol, Mandates, and Drought: Insights from a Stochastic Equilibrium Model of the U.S. Corn Market.” Working Paper 08-WP 464, Center for Agricultural and Rural Development, Iowa State University.

Meyer, S. and W. Thompson. 2010. “Demand Behavior and Commodity Price Volatility Under Evolving Biofuel Markets and Policies.” Chapter 9 in M. Khanna, J. Scheffran, and D. Zilberman (eds.), *Handbook of Bioenergy Economics and Policy*, Springer Science Verlag.

Pearson K. and C. Arndt. 2000. Implementing Systematic Sensitivity Analysis Using GEMPACK. GTAP Technical Paper No. 3, Purdue University.

Serra, T., Zilberman, D., Gil, J.M. and B.K. Goodwin. 2010a. “Price Transmission in the US Ethanol Market.” Chapter 5 in M. Khanna, J. Scheffran, and D. Zilberman (eds.), *Handbook of Bioenergy Economics and Policy*, Springer Science Verlag.

Serra, T., Zilberman, D., Gil, J.M. and B.K. Goodwin. 2010b. “Price Volatility in Ethanol Markets.” unpublished manuscript, Energy Bioscience Institute, University of California at Berkeley.

Taheripour, F., Birur, D. Hertel, T. and W.Tyner. 2007. “Introducing Liquid Biofuels into the GTAP Data Base.” GTAP Research Memorandum No. 11.

Taheripour, F., Hertel, T., Tyner, W., Beckman, J. and D. Birur. 2009 “Biofuels and Their By-products: Global Economic and Environmental Implications.” *Biomass and Bioenergy*, 33(3):278-289.

Thompson, W., Meyer, S. and P. Westhoff. "How Does Petroleum Price and Corn Yield Volatility Affect Ethanol Markets with and without an Ethanol Use Mandate?" *Energy Policy*, Vol. 37(2):pp745-749.

Tyner, W. 2009. "The Integration of Energy and Agricultural Markets." Presented at the International Association of Agricultural Economists, Beijing, China.

Ubilava, D. and M. Holt. 2010. "Forecasting Corn Prices in the Ethanol Era." unpublished manuscript, Department of Agricultural Economics, Purdue University.

Valenzuela, E., Hertel, T.W., Keeney, R. and J. Reimer. 2007. "Assessing Global Computable General Equilibrium Model Validity Using Agricultural Price Volatility". American Journal of Agricultural Economics, 89(2): 383-397.

Yano, Y., Blandford, D. and Y. Surry. 2010. "The Impact of Feedstock Supply and Petroleum Price Variability on Domestic Biofuel and Feedstock Markets – The Case if the United States." Swedish University of Agricultural Sciences, Working Paper:2010:3.

Tables and Figures

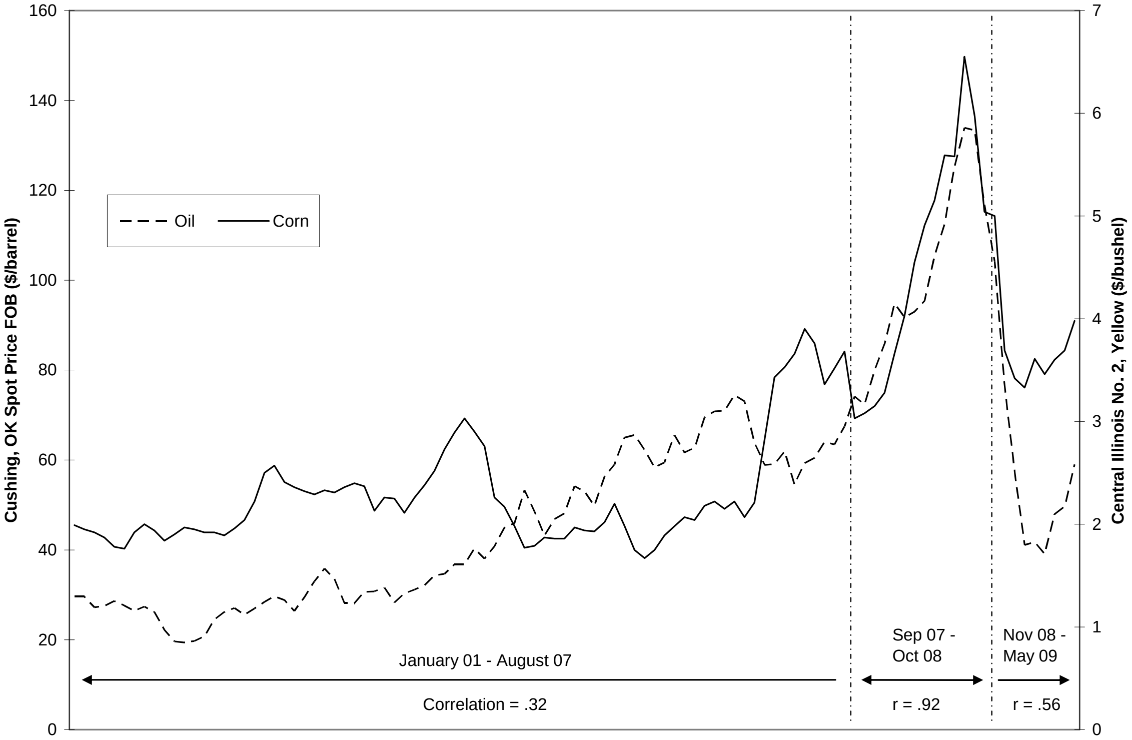
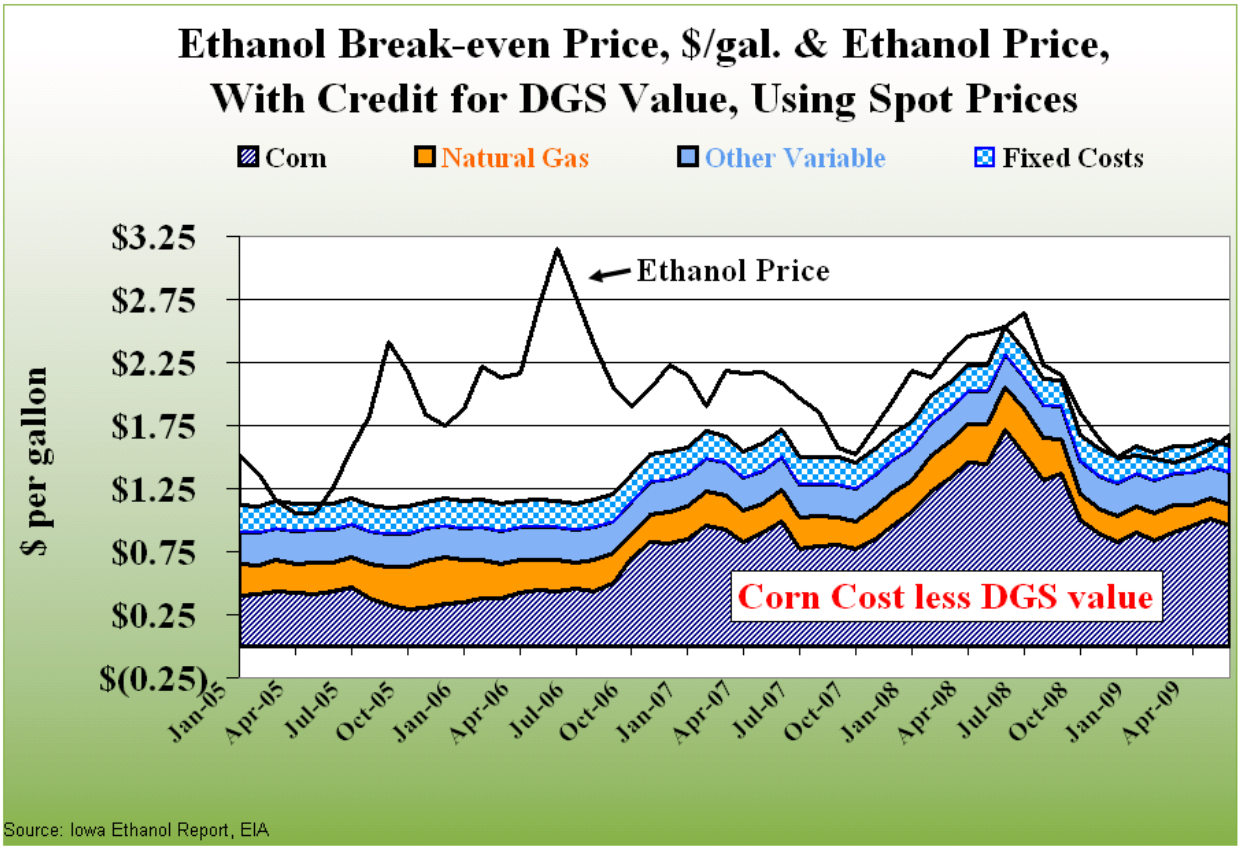


Figure 1. Monthly Oil (Cushing, OK Spot Price $/barrel) and Corn (Central Illinois No.2 Yellow $/bushel) Prices, January 2001 to May 2009



Source: Iowa Ethanol Report, EIA

Figure 2. Relationship between output and input prices in the ethanol industry over time: 2005 – April, 2009; Complied by Robert Wisner, Iowa State University

Table 1. AGE Model Parameters and Data

Time Period	σ	η_{FD}	α	β	Θ_{EC}	ν_{EC}
	Parameter					
2001	3.95	0.10	0.25	0.06	0.39	0.43
2008	3.95	0.10	0.44	0.26	0.67	0.31
2015	3.95	0.10	0.60	0.40	0.70	0.25

Source: Authors' calculations, based on the AGE model parameter file and data bases.

Table 2. Exogenous Shocks to Update the Data base

	Determinants of Economic Growth						
	Population	Labor Supply % Change		Capital	Investment	TFP	Real GDP
Region	% Change	Unskilled	Skilled	% Change	% Change	% Change	% Change
USA	6.0	9.0	8.1	35.3	24.5	1.5	24.5
CAN	5.3	10.7	9.9	28.7	20.3	0.8	20.3
EU27	0.5	2.0	2.9	21.2	15.8	1.2	15.6
BRAZIL	8.5	1.8	28.1	24.0	22.7	0.6	22.7
JAPAN	0.1	1.4	-3.4	22.1	15.1	1.8	15.1
CHIHKG	4.7	6.6	29.0	96.6	66.7	2.9	65.5
INDIA	10.3	13.3	41.5	54.5	51.2	3.8	51.2
LAEEX	10.0	11.0	41.2	21.0	20.5	-0.6	20.6
RoLAC	11.6	13.6	43.2	34.7	25.2	-0.1	25.2
EEFSUEX	-1.2	3.6	7.9	22.7	41.3	3.7	40.0
RoE	8.6	8.0	26.7	16.7	24.1	2.2	25.4
MEASTNAEX	13.8	18.1	33.4	32.8	32.7	0.8	31.3
SSAEX	16.0	20.5	28.8	32.9	32.8	1.7	30.1
RoAFR	6.7	12.9	16.8	12.9	26.0	2.1	25.2
SASIAEEX	9.2	17.4	48.7	40.5	38.8	1.7	38.1
RoHIA	3.8	-2.1	27.7	42.8	38.6	2.7	38.2
RoASIA	12.9	15.2	36.1	33.4	39.9	2.8	40.6
Oceania	8.6	11.6	8.5	32.1	27.3	0.2	27.3

Source: GTAP-Dyn and Model Results (TFP)

Table 3. Time-Series Residuals, Used as Inputs for the Stochastic Simulation Analysis

Region	Corn Production	GDP	Oil Price
United States	19.05	3.18	24.91
Canada	14.84	4.27	24.91
European Union	11.91	2.04	24.91
Brazil	16.34	2.52	24.91
Japan		1.81	24.91
China	14.32	6.01	24.91
India	16.54	3.55	24.91
LAEEX	13.54	3.27	24.91
ROLAC	8.64	4.36	24.91
EEFSUEX		1.58	24.91
RoE	15.72	1.38	24.91
MEAST	9.66	5.27	24.91
SSAEX	11.87	4.65	24.91
RoAFR		2.47	24.91
SASIAEEX		4.90	24.91
RoHIA	19.93	3.65	24.91
RoASIA	6.71	4.84	24.91
OCEANIA	16.80	1.88	24.91

Table 4. Model Generated Coarse Grain Price Variation in 2001, 2008, 2015 Economies

	2001 Model Volatility			2008 Model Volatility			2015 Model Volatility (Base-No RFS/BW)		
Region	All Shocks	Oil Price	Corn Production	All Shocks	Oil Price	Corn Production	All Shocks	Oil Price	Corn Production
USA	28.5	1.1 (.04)	27.5 (.96)	30.7	10.0 (.32)	28.7 (.93)	29.8	15.6 (.53)	25.1 (.84)
Canada	16.7	1.1 (.07)	16.2 (.97)	18.8	4.4 (.23)	18.0 (.96)	18.6	5.5 (.29)	17.7 (.95)
EU	18.3	1.0 (.05)	17.5 (.96)	20.4	3.1 (.15)	20.0 (.98)	20.2	3.2 (.16)	19.8 (.98)
Brazil	19.0	1.1 (.06)	18.8 (.99)	21.0	4.3 (.20)	20.7 (.99)	20.6	4.5 (.22)	20.3 (.99)
Japan	4.9	0.2 (.04)	3.8 (.77)	9.7	2.3 (.24)	8.9 (.92)	8.7	4.3 (.48)	7.6 (.88)
CHIHKG	34.0	0.1 (0)	32.4 (.95)	47.0	1.8 (.04)	46.4 (.99)	46.3	0.8 (.02)	46.0 (.99)
India	31.4	1.5 (.05)	31.1 (.99)	37.6	5.1 (.14)	36.9 (.98)	37.5	3.9 (.10)	36.9 (.98)
LAEEX	18.7	1.0 (.05)	18.1 (.97)	20.4	5.0 (.25)	19.8 (.97)	20.2	5.8 (.29)	19.5 (.97)
RoLAC	11.7	0.4 (.03)	11.0 (.95)	13.4	2.2 (.16)	12.8 (.96)	13.0	3.4 (.26)	12.5 (.96)
EEFSUEX	2.4	1.1 (.49)	0.7 (.29)	2.9	1.8 (.65)	1.5 (.54)	2.9	1.3 (.46)	1.5 (.52)
RoE	20.7	1.9 (.09)	20.4 (.99)	22.2	3.8 (.17)	22.2 (1.00)	22.0	3.7 (.17)	22.0 (1.00)
MEASTNAEX	11.4	3.4 (.29)	10.8 (.94)	14.7	10.2 (.70)	12.9 (.88)	14.9	8.8 (.59)	12.7 (.85)
SSAEX	2.8	2.6 (.92)	0.7 (.26)	6.1	9.5 (1.56)	1.0 (.17)	6.1	7.6 (1.25)	1.0 (.17)
RoAFR	3.0	0.6 (.19)	1.9 (.64)	5.4	2.1 (.39)	4.7 (.88)	5.3	2.9 (.55)	4.2 (.79)
SASIAEEX	5.4	0.2 (.03)	4.0 (.74)	6.4	0.5 (.07)	5.6 (.87)	6.2	1.0 (.16)	5.4 (.88)
RoHIA	4.8	0.6 (.12)	3.7 (.77)	6.1	1.0 (.16)	5.6 (.91)	5.6	1.8 (.31)	4.9 (.88)
RoASIA	12.3	0.4 (.04)	11.7 (.95)	13.3	1.1 (.09)	12.9 (.96)	13.1	0.3 (.02)	12.7 (.97)
OCEANIA	18.9	0.5 (.03)	18.5 (.98)	19.8	3.0 (.15)	19.1 (.96)	19.2	4.2 (.22)	18.6 (.97)
World Average	14.4			16.3			15.5		

Note: Parenthesis represent the share of volatility for oil price/corn production inputs in total volatility. Historical variation in corn prices for the U.S. was 21.6 standard deviations over the 1981-2008 time period.

Table 5. Model Generated Coarse Grain Price Variation in the 2015 Economy for the Base Case, Renewable Fuels Standard, and a Blend Wall

	RFS Binding			Blend Wall Binding			RFS and Blend Wall Binding		
Region	All Shocks	Oil Price	Corn Production	All Shocks	Oil Price	Corn Production	All Shocks	Oil Price	Corn Production
USA	37.1	9.5 (.26)	36.7 (.99)	31.6	6.7 (.21)	28.2 (.89)	40.4	1.2 (.03)	39.5 (.98)
Canada	19.6	3.8 (.19)	18.9 (.96)	18.7	3.1 (.17)	18.1 (.96)	19.9	1.8 (.09)	19.3 (.97)
EU	20.6	2.5 (.12)	20.2 (.98)	20.2	2.3 (.11)	19.8 (.98)	20.6	1.8 (.09)	20.2 (.98)
Brazil	21.1	3.5 (.16)	20.7 (.99)	20.7	3.2 (.15)	20.3 (.99)	21.1	2.3 (.11)	20.9 (.99)
Japan	10.7	2.2 (.20)	10.2 (.95)	10.1	1.6 (.16)	8.9 (.88)	12.1	0.3 (.03)	11.4 (.94)
CHIHKG	46.7	1.3 (.03)	46.1 (.99)	46.6	1.4 (.03)	46.0 (.99)	46.7	1.8 (.04)	46.1 (.99)
India	37.5	3.9 (.10)	36.9 (.98)	37.5	4.0 (.11)	36.9 (.98)	37.5	4.1 (.11)	36.9 (.98)
LAEEX	21.3	4.3 (.20)	20.7 (.97)	20.0	3.8 (.19)	19.7 (.98)	21.2	2.4 (.11)	20.9 (.99)
RoLAC	14.1	2.0 (.14)	13.6 (.97)	13.5	1.6 (.12)	12.8 (.95)	14.6	0.4 (.03)	14.0 (.96)
EEFSUEX	3.0	0.9 (.32)	1.8 (.60)	2.9	0.6 (.21)	1.6 (.55)	3.0	1.5 (.51)	1.9 (.62)
RoE	22.3	3.0 (.14)	22.3 (1.00)	22.0	2.9 (.13)	22.0 (1.00)	22.2	2.4 (.11)	22.3 (1.00)
MEASTNAEX	14.8	8.1 (.55)	13.0 (.88)	14.5	7.8 (.54)	12.8 (.88)	14.5	7.3 (.50)	13.0 (.00)
SSAEX	6.0	7.4 (1.24)	1.1 (.19)	6.0	7.4 (1.23)	1.0 (.17)	6.0	7.4 (1.22)	1.1 (.18)
RoAFR	6.3	1.9 (.30)	5.6 (.90)	5.7	1.6 (.27)	4.7 (.83)	6.8	0.7 (.11)	6.1 (.90)
SASIAEEX	6.7	0.4 (.06)	5.8 (.87)	6.4	0.3 (.05)	5.5 (.86)	6.9	0.2 (.02)	6.0 (.87)
RoHIA	6.4	0.8 (.13)	5.7 (.89)	6.2	0.7 (.11)	5.4 (.87)	7.0	0.2 (.04)	6.2 (.89)
RoASIA	13.4	0.8 (.06)	12.9 (.97)	13.3	0.9 (.07)	12.7 (.96)	13.5	1.3 (.10)	13.0 (.96)
OCEANIA	20.3	2.7 (.15)	19.3 (.95)	19.5	2.2 (.11)	18.9 (.97)	20.5	0.9 (.04)	19.7 (.96)
World Average	17.8			16.5			19.3		

Note: Parenthesis represent the share of volatility for oil price/corn production inputs in total volatility. Historical variation in corn prices for the U.S. was 21.6 standard deviations over the 1981-2008 time period.

Table 6. Mean Percentage Changes in Corn Price and Ethanol Production in 2015 under the Different Stochastic Scenarios

Scenario	Mean Percentage Price Change	Mean Percentage Change in Ethanol Production
Base Case	8.9	3.7
RFS	18.7	22.8
BW	2.1	-21.1
RFS/BW	12.2	0

Appendix A1
Industries, Commodities, and their Corresponding GTAP Notation

Industry Name	Commodity Name	Description	GTAP Notation
CrGrains	CrGrains	Cereal Grains	gro
OthGrains	OthGrains	Other Grains	pdr, wht
Oilseeds	Oilseeds	Oilseeds	osd
Sugarcane	Sugarcane	Sugarcane and sugarbeet	c_b
Cattle	Cattle	Bovine Cattle, sheep and goats	ctl, wol
Nonrum	Nonrum	Non-ruminants	oap
Milk	Milk	Raw Milk	rmk
Forestry	Forestry	Forestry	frs
Ethanol2	Ethanol2	Ethanol produced from sugarcane	eth2
OthFoodPdts	OthFoodPdts	Other food products	b_t, ofdn
VegOil	VegOil	Vegetable oils	voln
ProcLivestoc	ProcLivestoc	Meat and dairy products	cmt, mil, omt
OthAgri	OthAgri	Other agriculture goods	ocr, pcr, pfb, sgr, v_f
OthPrimSect	OthPrimSect	Other primary products	fsh, omn
Coal	Coal	Coal	coa
Oil	Oil	Crude oil	oil
Gas	Gas	Natural gas	gas, gdt
Oil_Pcts	Oil_Pcts	Petroleum and coal products	p_c
Electricity	Electricity	Electricity	ely
En_Int_Ind	En_Int_Ind	Energy intensive industries	crpn, i_s, nfm
Oth_Ind_Se	Oth_Ind_Se	Other industry and services	atp, cmn, cns, dwe, ele, fmp, isr, lea, lum, mvh, nmm, obs, ofi, ome, omf, osg, otn, otp, ppp, ros, tex, trd, wap, wtp, wtr
EthanolC	Ethanol1	Ethanol produced from grains	eth1
	DDGS	DDGS	ddgs
Biodiesel	Biodiesel	Biodiesel	biod
	BDBP	BDBP	bdbp

Appendix A2

Regions and their Members

Region	Corresponding Countries in GTAP
USA	United States
CAN	Canada
EU27	Austria; Belgium; Bulgaria; United Kingdom; Cyprus; Czech Republic; Germany; Denmark; Spain; Estonia; Finland; France; Greece; Hungary; Ireland; Italy; Lithuania; Luxembourg; Latvia; Malta; Netherlands; Poland; Portugual; Romania; Slovakia; Slovenia; Sweden
BRAZIL	Brazil
JAPAN	Japan
CHIHKG	China and Hong Kong
INDIA	India
LAEEX	Argentinal; Columbia; Mexico; Venezuela
RoLAC	Chile; Peru; Uruguay; Rest of Andean Pact; Central America; Rest of the Caribbean; Rest of Free Trade Area of the Americas; Rest of North America; Rest of South America
EEFSUEX	Russia; Rest of EFTA; Rest of Former Soviet Union
RoE	Albania; Switzerland; Croatia; Turkey; Rest of Europe
MEASTNAEX	Botswana; Tunisia; Rest of Middle East; Rest of North Africa
SSAEX	Madagascar; Mozambique; Malawi; Tanzania; Uganda; Rest of South African Customs Union; Rest of Southern African Development Community; Rest of Sub-Saharan Africa; Zimbabwe
RoAFR	Morocco; South Africa; Zambia
SASIAEEX	Indonesia; Malaysia; Vietnam; Rest of Southeast Asia
RoHIA	Korea; Taiwan
RoASIA	Bangladesh; Sri Lanka; Philippines; Singapore; Thailand; Rest of East Asia; Rest of South Asia
Oceania	Australia; New Zealand; Rest of Oceania