Draft: February 16, 2010

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

Thomas W. Hertel*
and
Jayson Beckman†

*Distinguished Professor and Executive Director, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, 403 W. State St., West Lafayette, IN 47907, phone: 765-494-4199, email: hertel@purdue.edu
†Economist, ERS/USDA, email: jbeckman@ers.usda.gov.

Paper prepared for the NBER Agricultural Economics Conference, March 4-5, 2010, Cambridge, Mass.
The authors thank Roman Keeney and Wally Tyner for valuable discussions, suggestions and insights on this topic

Abstract

Agricultural and energy commodity prices have traditionally exhibited relatively low – even negative correlation. However, the recent increases in biofuel production have altered the agriculture-energy energy relationship in a fundamental way. The amount of corn utilized for ethanol production in the US has increased from 5% in 2001 to over one-third by the end of the decade. This increase has drawn corn previously sold to other uses (exports, food, feed), as well as acreage devoted to other crops (e.g., oilseeds and other grains). In addition, there has been an increase in the demand for production inputs, especially fertilizers, which are heavily energy-intensive. In short, the previous "biofuel decade" has led to significant changes in the US, and indeed the global economy.

In the next five years, the U.S. Renewable Fuels Standard (RFS) envisions a further boost of ethanol production to 15 billion gallons per year. This might be expected to further strengthen the linkage between energy prices and agricultural commodity markets. However, unless oil prices rise sharply, it is likely that the RFS will be binding in 2015 – that is, the amount of ethanol consumed will be determined by government mandates rather than by the relative price of oil vs. corn-based ethanol. Under such a scenario, with an even larger share of corn production going to ethanol, and with that source of demand potentially becoming unresponsive to price, there is potential for significant increases in commodity market volatility. Indeed, 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, we expect that, rather than the RFS binding, the binding constraint is likely to be the "blend wall", i.e. the legal % content of ethanol in gasoline used by regular automobiles. (This is currently set at 10%.) With a binding blend wall, we see similar, although somewhat smaller, increases in market volatility. If both the RFS and the blend wall are simultaneously binding, then 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%. In short, we envision a future in which agricultural price volatility – particularly for biofuel feedstocks – will depend critically on renewable energy policies. Indeed, these may dominate the traditional importance of agricultural commodity policies in many markets.

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

Introduction

U.S. policy-makers have responded to increased public interest in reducing greenhouse gas (GHG) emissions and lessening dependence on foreign supplies of energy with Renewable Fuels Standard (RFS) that impose 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; Chantret and Gohin; 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 agriculture is fundamentally different at high oil prices vs. at 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 .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 (.92, see Figure 1 again), with corn prices/bushel 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 have fallen, 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, an excess supply of ethanol began to emerge in many regional markets (due to infrastructure limitations there is not a single national market for ethanol). This has led to a separation of the ethanol and oil prices, with the 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 of Figure 1 is much weaker (.56).

In this paper, we develop a framework specifically designed for analyzing the linkages between energy and agricultural markets under different policy regimes. 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 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, we find that, by 2015, the contribution of energy price volatility to year-on-year corn price variation will be much greater – 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-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 would boost the sensitivity of corn prices to supply side shocks by nearly 50%. Similar results ensue in the presence of a binding blend wall.

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 around 70-80% of the total costs used to manufacture fertilizers. Additional linkages

come in the form of transportation of inputs, as well as the use of diesel or gasoline on-farm or in the transportation of commodities. Overall, USDA/ERS *Cost of Production* estimates indicate that energy inputs account for almost 30% of the total cost of corn production for the US in 2008[1].

Another important linkage to energy markets is on the output side, as agricultural commodities are increasingly being used as feedstocks for biofuels used in liquid fuels. 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 by the petroleum refining industry. In the EU, they estimate that biodiesel growth over the same period was more heavily influenced by subsidies. Nonetheless, oil price increases those authors estimate that oil price increases accountec for about two-fifths of the expansion in EU biofuel production over the 2001-2006 period.

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 (-.26) from 1988-2005; in contrast, it reached a value of .80 during the 2006-2008. And, as Figure 1 shows, focusing on monthly data from September 2007-October 2008 yields a correlation of 0.92.

[1] Comparing the COP 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%.

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.

Based on this evidence it is clear that the strong link between crude oil prices and corn prices is a recent phenomenon; hence, econometric investigations of price transmission —particularly with annual or monthly data are problematic. Rather, stochastic simulation has been the primary vehicle to examine this topic. 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% s.d. (i.e., if prices are normally distributed, 68% of the time the gasoline price will be within $\pm$ 25% of the mean gasoline price) would lead to volatility in the corn price of 17.5% s.d.

Thompson et al. (2009) also utilized a stochastic framework (based on the FAPRI model) to examining how shocks to the crude oil (and corn) markets can affect ethanol price and use. They note that the RFS provides 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 .31 (i.e., a 1% increase in the price of oil leads to a .31% increase in the corn price) with no RFS, and .17 with the RFS.

This brief literature review 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. 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 exposition, and to be consistent with the general equilibrium specification introduced later on, we will think of 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 to these two functions, we can clearly specify the market shares governed by the two different types of behavior.

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:

$$q_E = (1-\alpha)qa_E + \alpha qp_E \quad (2)$$

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):

$$qa_E = q_F \quad (3)$$

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:

$$qp_E = qp_F - \sigma(p_E - p_F) \quad (4)$$

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:

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

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 (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 empirical model) 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:

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

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:

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

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:

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

The term in brackets $\{.\}$ is ν_{CE}, the *net* supply elasticity of corn to the ethanol sector. 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. These shocks are larger, the 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 partial equilibrium model for equilibrium in the corn ethanol market. To do so, we make a number of simplifying 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, 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):

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

Recalling the following:

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

it is clear that a random shock to the non-ethanol, corn market (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. In this case the expression for the corn price as a function of Δ_{CS} (substituting (20) into the denominator and numerator) becomes:

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

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

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

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.

Now consider the impact of increasing β on the volatility of corn price in response to a (non-ethanol) corn demand shock. Substitution and reorganization yields the following expression:

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

The presence of $(1-\beta)$ in the numerator means that higher values of β reduce 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 result 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 ($\eta_{FD} < 0$) such that the entire denominator in (24) becomes. (Given the relatively inelastic demand for liquid fuels for transportation, this seems virtually impossible.) 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 supply (Δ_{CS}) 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 a larger 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 price volatility in response to a 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 market's response to a supply side shock.

Proposition 2: A random shock to the non-ethanol corn 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 a larger share of corn going to ethanol (β) is unambiguous when ethanol demand is more price responsive than other demand – it serves to lessen the volatility in corn prices with respect to a shock in non-ethanol demand. When ethanol demand is not price responsive (e.g., due to a blend wall), then an increase in sales to ethanol may destabilize the corn market's response to a shock to non-ethanol demand.

Proposition 3: 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 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 4: 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 is 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 fifth, and final, proposition.

Proposition 5: The 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 is 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 propositions 1 – 5 continue to offer useful insights into the 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 the kind of analytical and empirical insight needed at this point in the debate on biofuel policy impacts. The value of a global, AGE approach in analyzing the global trade and land use impacts of biofuel mandates has previously been demonstrated in the work of Banse et al. (2008), Chantret and Gohin (2008), 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) insight into 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 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 (2009) 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 (taken from Valenzuela et al., 2007) by adding volatility in energy markets (specifically oil) and in aggregate demand (as proxied by volatility by national GDPs) following Beckman, Hertel, and Tyner (2009). 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 market feedback effects. To capture the resulting feedback 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, Tyner, 2009). 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 following Beckman, Hertel, and Tyner (2009) to update the model to 2008. 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 result is a reasonable approximation to key features of the more recent economy.

The updating of the model 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 economy, and observe the estimated corn price variation. As Figure 1 illustrated, the 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 the empirical dimensions of propositions 1-3 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 U.S. ethanol production to 15 billion gallons/year. We do not run a full update experiment (as we did for the 2001-2008 time period) as we do not know exactly how the key exogenous variables will evolve over this future period.[2] 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 focus on 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 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,

[2] 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).

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 been increased from 10% to 12 or 15%). 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 5 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 demand, namely GDP, allowing the GDP 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, times-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[3]. 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. Demand-side shocks also play a role in determining commodity price volatility. Here, we use the variation in regional Gross Domestic Product (GDP) to capture changes in aggregate demand in each of the markets.

The key result 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[4]. 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 multiplied by 100%. Not surprisingly, from table 3, we see that corn production and oil

[3] 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.
[4] Estimates for the time-series models are available upon request.

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 US 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 estimates 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 s.d. 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 3). This confirms the findings of Tyner (2009) who reports almost no 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 (s.d. 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 AGE models for 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 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 reduces, 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 mandates that 15 billion gallons of corn ethanol be produced by 2015, up from the little more than 7 billion gallons produced in 2008 (this is known as the Renewable Fuel Standard (RFS)). We implement this mandate by increasing US ethanol production through a quantity increase, following Hertel, Tyner, and Birur (2010).

Mathematically, the RFS 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, 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:

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

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

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 taxing the combined liquid fuel product by the amount of the subsidy.

The key point about the RFS is that it is asymmetric. Thus, when the RFS is just binding ($S > 0, (QR_{RFS} - 1) = 0$, a further rise in the price of gasoline will increase

ethanol production past the mandated amount, as ethanol is better able to compete with gasoline on an energy basis. In contrast, a decrease in the price of gasoline does nothing to ethanol production (i.e., it says at the 15 billion gallon mark) as this is the mandated amount and so $S > 0$ ensures that the ethanol continues to be used at current levels.

A blend wall works differently from the RFS; as pointed out by Tyner (2009), the blend wall is an effective constraint on demand[5]. 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 required to restrict additional use of ethanol, and QR is the ratio of observed ethanol intensity (Q_E / Q_F) to the blend wall (currently 0.10 in theory, but less in practice due to the regionalization of markets):

$T \geq 0 \perp (1 - QR_{BW}) \geq 0$ 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 binding so that $T = 0, (1 - QR_{BW}) = 0$, while the RFS is not binding. Then if the price of gasoline were to rise, ethanol production would not change since it is up against the blend wall. The tax would simply adjust to ensure the constraint remains binding. However, if the price of

[5] 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%.

gasoline falls, ethanol production declines, thereby moving off this constraint and falling to the point where the RFS becomes binding.

With these alternative policy regimes in mind, we investigate the importance of energy price shocks on agricultural commodity prices under four different scenarios:

1) Base case: the RFS is not binding; and there is no blend wall. This should generate the greatest importance of energy price shocks on agricultural commodity price volatility. Results from this case are reported in the last part of Table 4.
2) RFS is binding, i.e., ethanol production can not fall below 15 billion gallons, but if oil prices are large enough, ethanol demand can be utilized past the 15 billion gallon mark. Here coarse grains demand is more inelastic; commodity price volatility is greater in the wake of the supply-side shocks, but not as responsive to energy price shocks as it was in the base case. Results from this and the subsequent experiments are reported in Table 5.
3) RFS is not binding; however, the blend wall is binding. We expect the impact of energy price shocks on commodity price volatility to be lowest in this case, as ethanol production will not be able to expand as readily to high oil prices because of the blend wall.
4) Both RFS and blend wall are binding. This could happen if the blend wall were adjusted just enough to permit the RFS to be met.

Results for the 2015 base case (Table 4) indicate that, relative to the 2008 data base, energy price shocks contribute more to coarse grain price variation. Indeed, energy price volatility now contributes to a s.d. of 15.6, or 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 as compared to the 2008 data base. In addition, ethanol production is free to respond to low and high oil price draws from the stochastic simulations, since there is not an RFS or blend wall in place. The contribution of corn production 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 sims; however, we assume that the RFS is 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 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); due to the fact that we truncate the ability of the model to respond to low energy price draws by using less ethanol. The implementation of the RFS also leads to highest much higter variation in corn prices. In proposition 4, 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 production and non-ethanol demand.

For the third scenario, we allow the RFS to be non-binding, but we implement a blend wall, which is assumed to be just binding. The results from this case indicate that the share of energy price volatility to total corn price variation is at an even lower level. 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 binding. The 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, corn price volatility in the face of the very same 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 binding energy policies have the potential to greatly destabilize agricultural commodity markets in the future.

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 did strengthen the transmission of energy price volatility on agricultural commodity price variation. Furthermore, the additional mandated production will go further in

strengthening this transmission. However, policy regimes are going to play a critical role in determining the nature of this linkage. 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 disjoint in the transmission of energy prices to agriculture, as well as increasing commodity price volatility.

Comparing the three scenarios, having no biofuel policy leads to the highest transmission of energy price volatility on commodity price variation and the lowest impact from corn production volatility. This is because the model is able to respond to both high and low oil prices; and corn production shocks are spread out across all sectors, minimizing the potential impacts. When we implement a specific policy (either the RFS or a blend wall), the impacts from energy price volatility are smaller than the base case as a portion of the model is essentially shut off (either from low or high oil prices). The impacts from corn production volatility are magnified in the presence of the policy regimes as half of corn allocation is removed from possible variation.

In the most extreme case, wherein both the RFS and the blend wall are simultaneously 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%. In short, we envision a future in which agricultural price volatility – particularly for biofuel feedstocks – will depend critically on renewable energy policies. Indeed, these may dominate the traditional importance of agricultural commodity policies in many markets.

References

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

Beckman, J., T.W. Hertel, and W.E. Tyner, (2009). "How Valid are CGE Based Assessments of Energy and Climate Policies?", under third round review with *Energy Economics*.

Chantret, F. and A. Gohin. 2009. "The Long-Run Impact of Energy Prices on World Agricultural Markets: The Role of Macro-Economic Linkages." Presented at the International Agricultural Trade Research Consortium, Seattle, Washington.

Du, X., Yu, C. and D. Hayes. "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.

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

Hertel, T., A. Golub, A. Jones, M. O'Hare, R. Plevin 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.

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.

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

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., Birur, D. 2009 "Biofuels and Their By-products: Global Economic and Environmental Implications. *Biomass and Bioenergy* (in press).

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.

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.

Tables and Figures

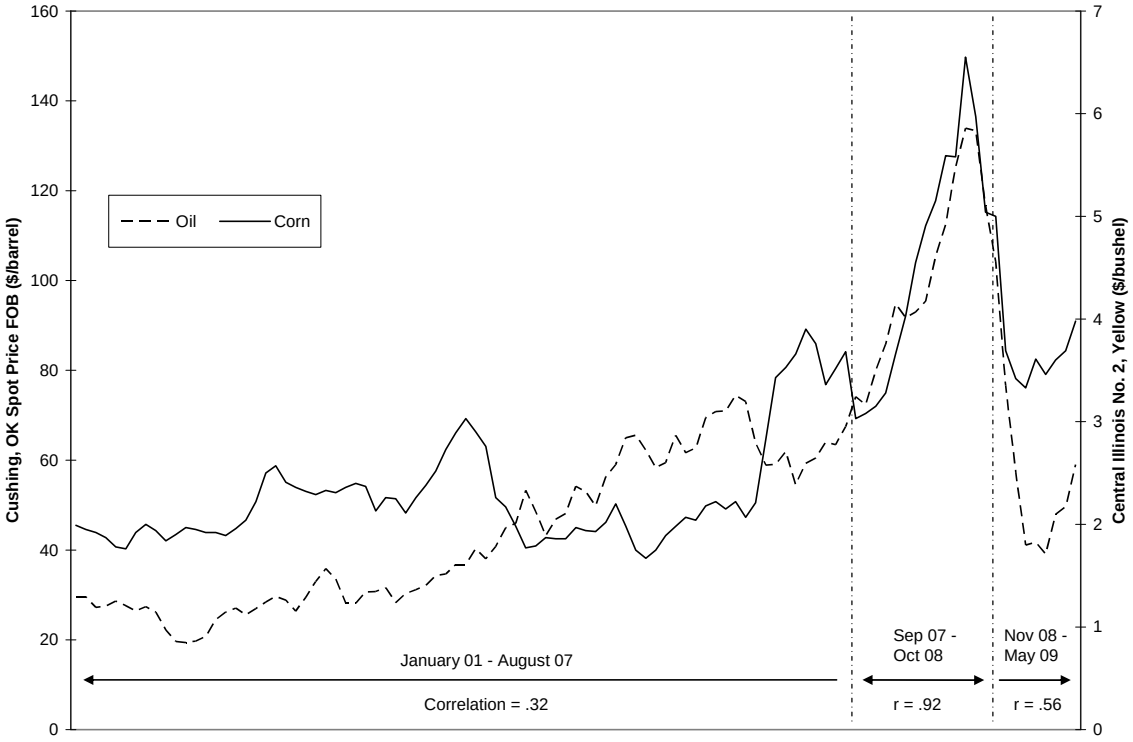


Figure 1. Monthly Oil (Cushing, OK Spot Price $/barrel) and Corn (Central Illinois No.2 Yellow $/bushel) Prices, January 2001 to May 2009

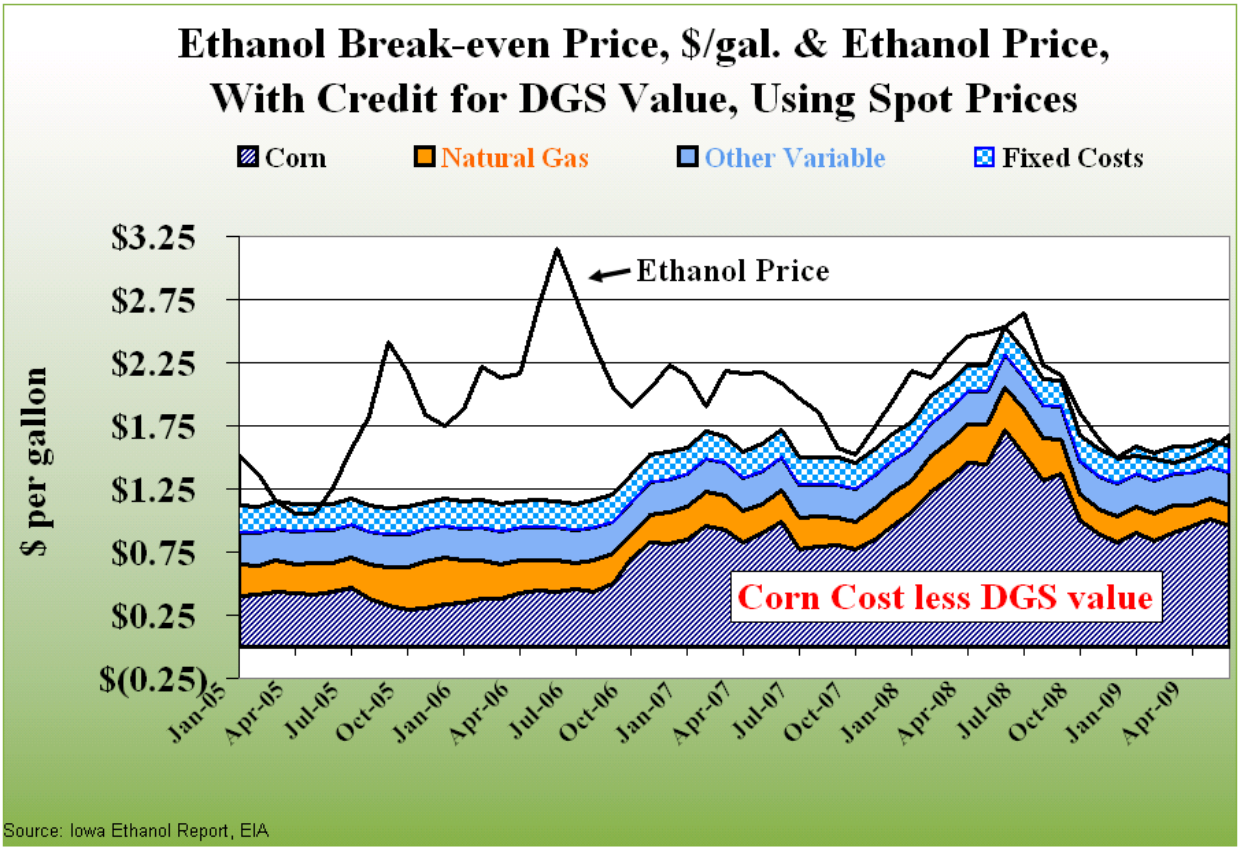


Figure 2. Relationship between output and input prices in the ethanol industry over time: 2005 – April, 2009; Complied by Robert Wisner, Iowa State University

Table 1. AGE Model Parameters and Data

	Parameter					
Time Period	σ	η_{FD}	α	β	Θ_{EC}	ν_{EC}
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.

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