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How Market Efficiency and the Theory of Storage Link Corn and Ethanol Markets

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Abstract

In this article we use the theories of market efficiency and supply of storage to develop a conceptual link between the corn and ethanol markets and explore statistical evidence for the link. We propose that a long-run no-profit condition is established in distant futures markets for ethanol, corn, and natural gas and then use the theory of storage to define an inter-temporal equilibrium among these prices. The relationship shows that under certain conditions, future price expectations will influence current spot prices and that a short-term relationship between input and output prices will exist. This short-term relationship will contain fixed costs. We demonstrate validity of the theory using a structural price model and then by means of time-series techniques.

Keywords: arbitrage, cointegration, corn, energy, ethanol, futures, price-analysis, storage.

HOW MARKET EFFICIENCY AND THE THEORY OF STORAGE LINK CORN AND ETHANOL MARKETS

Thanks to a combination of favorable market conditions and government support, over a third of the U.S. corn crop currently is used to produce ethanol, and ethanol production recently overtook exports as the second-largest use category of corn behind feed and residual use.¹ Since ethanol production is such a large factor in corn demand, the price of corn should respond to the fundamentals of ethanol markets much as it responds to the fundamentals of agricultural markets. This linkage is not only central to agricultural markets but also has profound implications for the entire agricultural sector. If high energy prices translate into high prices for ethanol, then prices for corn and crops that compete with corn for acres will move in line with energy prices.

This article uses the theories of market efficiency and supply of storage to develop a conceptual link between the corn and ethanol markets and explores statistical evidence for the link. Unlike previous studies, we propose that the link between the corn and the energy sectors is manifest in *futures* prices at least one year to maturity. Previous studies have focused on the link in spot (or nearby futures) markets, with disappointing predictive ability. Our contribution recognizes that the link between corn and ethanol prices should come about from a long-run no-profit condition; therefore, the link is established in forward prices. Once we have established this long-run relationship, cost-of-carry arbitrage conditions that are specific to the corn, ethanol, and natural gas futures markets are used to calculate a spot corn price forecast. Because the no-profit condition is long-run in nature, our equilibrium condition includes fixed costs. To the best of our

knowledge, it is the first time a long-run relationship that includes fixed costs has been used to motivate short-run, daily price co-movements.

Our results lend strong support to the forward equilibrium hypothesis even through the recent ups and downs of corn and ethanol prices. This relationship began in mid-2006 and it has continued to at least the fall of 2010. This relationship appears to be sufficiently strong to dominate all other forces at play in setting the relationship between corn and ethanol prices in recent years.

We perform cointegration analyses to econometrically test our hypothesis. These tests lend support for the case that corn, ethanol, and natural gas prices are in fact governed by a breakeven relationship. Further, these tests indicate that the breakeven relationship is not maintained in the spot market but rather in the futures markets for ethanol, natural gas, and corn one year to maturity. The methodology we propose here has application to other sectors such as soybean processing or cattle feeding where the industry is competitive in the long-run.

Previous Work

Recent research has attempted to pin down the relationship between energy and agriculture created by corn-based ethanol production. Early work recognized that a long-run no-profit condition is likely to govern the price relationship between ethanol and its components. Then, if one is willing to assume that the price of ethanol and its non-corn components are exogenous to corn prices, one can solve for the long-run equilibrium price of corn.

De Gorter and Just (2008, 2009) developed a model of the corn and fuel markets focused on welfare analysis with a long-run equilibrium relationship tying the two sectors together in their model. This work pointed out that when the intercept of the ethanol supply curve is above what would be the market price of ethanol without any tax credit, much of the tax credit is redundant (de Gorter and Just 2008, 2009).

Tokgoz et al. (2007) first used the model maintained by the Food and Agricultural Policy Research Institute (FAPRI) to make long-run projections of the effect of biofuel production on commodity prices and production. They used the model again (Tokgoz et al. 2008) to simulate the effect of an exogenous event in one market on other markets; in particular, they explored the effect of a spike in crude oil price and the effect of a significant drought coupled with a renewable fuels mandate. These studies both relied on a long-run equilibrium condition in the ethanol market to transmit shocks in the ethanol market to the corn market.

This early research on the price implications of ethanol production clearly implied a belief on the part of the researchers that the price of corn and ethanol should be bound by a no-profit relationship. However, this hypothesis was not well supported by the data. As de Gorter and Just note, the long-run no-profit condition implies a linear relationship between corn and ethanol prices with a slope of approximately four. Figure 1 displays the ratio of weekly central Illinois corn prices and ethanol prices at Iowa plants² from January 26, 2007, to October 29, 2010. It shows that this relationship historically has had an average slightly larger than two and has not come close to four.

In an attempt to better explain spot prices in the corn and ethanol markets, Kruse et al. (2007) used a medium-run relationship to analyze the effect of removing biofuel

subsidies, and Thompson, Meyer, and Westhoff (2009) in a similar analysis examined the covariance among corn, ethanol, and oil markets. Instead of assuming that a long-run no-profit condition holds, they specified ethanol supply and demand functions that depend on capacity, which requires the assumption that the ethanol market gravitates toward a long-run equilibrium in the corn and ethanol markets.

Several studies have taken a more empirical approach to investigating linkages between corn and energy markets. Higgins et al. (2006) conducted a cointegration analysis of spot prices of ethanol, gasoline, natural gas, crude oil, and the fuel oxygenate MTBE. They found four cointegrating relationships, but corn, ethanol, and natural gas did not make up any of the unique relationships they identified.

Serra et al. (2008) used a threshold vector error correction model to estimate the cointegration of corn, ethanol, and crude oil nearby futures prices. The error correction model allowed them to estimate a long-run relationship—the error correction vector(s)—as well as short-run impacts of price relationships. They included threshold effects to capture possible nonlinearities in the relationship, which, they argued, may come about because of distribution bottlenecks or other factors. They found a single cointegrating relationship among the variables considered.

Harri, Nalley, and Hudson (2009) used the cointegration framework to analyze whether or not there is a long-run equilibrium relationship between exchange rates, crude oil prices, and corn spot prices. They found one cointegrating relationship but noted that previous research highlighted the effect of exchange rates on crude oil. It is therefore difficult to determine if this relationship was picked up because of the relationship

between crude oil prices and exchange rates, or if corn is truly part of the equilibrium relationship.

Wu and Guan (2009) used a GARCH-type model to capture volatility spillover between the crude oil and corn markets. This assumption implied a belief that the link between corn and energy markets comes through the error term if such a link exists. Zhang et al. (2010) performed a cointegration analysis of global commodity prices. They analyzed crude oil, gasoline, ethanol, corn, soybeans, wheat, sugar, and rice spot prices, finding no long-run relationship between the energy and agricultural commodities. Only short-run effects were significant between the two groups.

Taking these studies as a whole, there seems to be a disconnect between economic theory, which predicts a long-run no-profit condition to dominate the pricing relationship between corn and ethanol, and the empirical literature. The empirical studies are mixed as to whether a cointegrating relationship is present between corn and energy prices, and when a cointegrating relationship is found, it is often not appropriate to view it as support for a long-run no-profit condition because of the specific variables included in the model.

In this study, we explain some of this disparity. We argue that a no-profit condition must be maintained by the corn and ethanol markets, and we provide an equation for it similar to the one used by de Gorter and Just. Next, we show how this relationship should be established in distant futures prices—not in spot prices. We describe how storage allows the price relationship to be transmitted through the forward curve back to the spot price. Then we bridge the existing literature by illustrating the empirical performance of this simple structural model and by demonstrating statistical support using cointegration analysis.

A Theory of the Link between the Corn and Ethanol Markets

The logic of an equilibrium relationship between the corn and ethanol markets is based on a simple long-run no-profit condition for a competitive industry. If the price of corn and ethanol are such that ethanol plants make positive economic profits, then ethanol production can be expected to expand, causing the zero-profit condition to hold once again. The opposite can be expected when economic profits are below zero; ethanol production will decrease causing the price of corn and ethanol to adjust so the zero economic profit condition holds. We cannot expect this zero profit relationship to be maintained in the short run, since it takes time to build ethanol plants and expand the industry. This break-even condition should therefore impose a *long-run* equilibrium relationship between the price of corn and the price of ethanol if the ethanol industry is large enough and reasonably competitive in structure. We expand on this theory and describe the mechanism by which a forward-looking relationship between corn and ethanol prices can be transmitted to spot prices.

The long-run zero economic profit or break-even rule is that *Total Revenue - Total Cost = 0*. This is expressed in more detail by the following equation:

$$(1) \quad p_T^{eth} = p_T^c \left(1 - \frac{17}{56} * 0.91\right) / 2.8 + p_T^{ng} + VC_{-corn} + FC.$$

where the revenue from producing a gallon of ethanol at T is p_T^{eth} . The use of T is to remind us that we expect this relationship to hold in the long run, or some date T , which is sufficiently far in the future. Note that Tokgoz et al. links corn prices to crude oil prices whereas our model links corn to ethanol. The Tokgoz approach requires understanding how the ethanol tax credit is passed from blender to ethanol producer as well as how

ethanol production impacts gasoline prices relative to crude oil prices. Our equilibrium relationship eliminates these uncertainties by focusing on the input and output of ethanol plants.

On the right-hand side of equation (1) are costs of ethanol production, which include the price of corn at time T , p_T^c , and the per gallon price of natural gas, p_T^{ng} . Natural gas is a common input in ethanol production used to dry distillers grains, the ethanol production co-product. Since the price of natural gas is highly variable and a significant share of the per gallon cost of producing ethanol, it is a major determinant of the profitability of an ethanol plant. We separate natural gas cost from the other costs of ethanol production so that profitability can vary with this input price.

The remaining per gallon non-corn, non-natural gas variable costs of producing ethanol are denoted by VC_{-corn} , assumed to be \$0.26 per gallon. Fixed costs are denoted by FC and assumed to be \$0.19 per gallon.³ These non-feedstock and non-natural gas costs are kept constant over the sample period. Hettinga et al. (2009) find that processing costs in ethanol production excluding these factors have remained relatively constant since around 2000.

We assume the ethanol yield per bushel of corn is 2.8 gallons per bushel, which is the conversion factor used in the USDA Market News reports of *Ethanol Corn and Co-Products Processing Values*.⁴ This lies between the ethanol yields reported in Perrin, Fulginiti, and Sesmero (2009) of 2.86 gallons per bushel and reported in Shapouri et al. (2010) of 2.76 gallons per bushel.

The term $(1 - 17/56*0.91)$ in equation (1) comes from the fact that the corn-based ethanol production process generates a co-product, distillers grains, which is used as a

feed that substitutes for corn and soybean meal in animal feed rations. For every bushel of corn (56 lbs) processed, an ethanol plant produces about 17 lbs of distillers grains. Distillers grains contain approximately the same energy content as corn and also contribute protein to livestock feed rations. Thus, distillers grains are valuable as an alternative livestock feed (Shurson et al. 2003). This means an ethanol plant's feedstock cost is not the full price of corn times the number of bushels of corn processed; e.g., if distillers grains are valued at par with corn, then for every bushel of corn processed, ethanol plants only have to pay for $(1 - 17/56)$ times the price of a bushel of corn. The remaining $(17/56)$ would come back to them when they sell the distillers grains. Anderson, Anderson, and Sawyer (2008) show that distillers grains prices are highly correlated with corn prices and that the price of distillers grains as a percentage of the corn price is approximately 91%. Therefore, in equation (1), $(1 - 17/56)*0.91$ accounts for the distillers grains co-product revenue; this reflects our assumption that distillers grains are valued at 91% of the price of corn.

Solving for the price of corn in the break-even rule in equation (1) we get an expression for the break-even energy value (*BEV*) of corn in \$/bushel:

$$(2) \quad p_T^{c, BEV} = 2.8 \left[p_T^{eth} - p_T^{ng} - VC_{-corn} - FC \right] / \left[\left(1 - \frac{17}{56} * 0.91 \right) \right].$$

Given the price of ethanol and natural gas at time T , this is the price of corn that would make an ethanol plant just break even, in the sense of covering all variable and fixed costs of production.

Futures Prices

If corn and energy futures markets are efficient (in the sense of Fama 1970 and Malkiel 2003), deviations from the equilibrium relationship between corn and ethanol prices posited by equation (1) cannot be violated in the long run. Therefore, far-to-maturity futures contracts should provide a signal to the ethanol industry to expand or contract so as to ensure no long-run profits or losses. Speculators in futures markets should recognize this opportunity and take positions that allow them to gain when the relative prices of corn and ethanol return to their equilibrium relationship. If these speculators observe a situation in which corn in the future has an expected energy value that is greater than current futures or forward prices, then they will go long in the appropriate number of corn contracts and short in ethanol contracts.

Denote the time t futures price of ethanol for delivery at time T by $F_{t,T}^{eth}$ and the time t futures price of natural gas for delivery at time T by $F_{t,T}^{ng}$. The presence of traders who take positions based on the spread between the corn and ethanol price means that the time t expected break-even energy value (*EBEV*) of corn at time T ,

$$(3) \quad P_{t,T}^{c,EBEV} = 2.8 \left[F_{t,T}^{eth} - F_{t,T}^{ng} - VC_{-com} - FC \right] / \left[\left(1 - 17/56 * 0.91 \right) \right],$$

should be approximately the actual futures price for corn of the same expiration, or, in other words, $F_{t,T}^c \approx P_{t,T}^{c,EBEV}$.

Since ethanol futures contracts only trade actively in delivery months up to about one year out, we use ethanol, corn, and natural gas futures prices one year to maturity to represent the long run (time T). For example, if July 2010 is the current nearby ethanol futures contract, then $F_{t,T}^{eth}$ is the July 2011 ethanol futures contract. Ethanol futures

contracts are thinly traded; if they do not sufficiently reflect expected future spot prices, then they would be of limited usefulness in this analysis and we would need to seek a proxy such as gasoline prices. In light of this thinness of market trading, it is surprising that Dahlgran (2009) finds that a direct hedge with ethanol futures is more effective than a cross-hedge with gasoline futures for hedging ethanol production margins. Further, he finds that this is especially true over longer hedging horizons. This result seems puzzling, but Dahlgran contends that an active over-the-counter swap market for ethanol and the bidirectional exchange for risk provision facilitates good price discovery in the ethanol futures contract. The exchange for risk provision allows a swap contract to be converted into a futures position and a futures position to be converted into a swap contract.

We will use ethanol futures prices throughout our analysis and also provide evidence that for our purpose the ethanol futures prices are more useful than gasoline futures prices. The data used are daily nearby and daily one-year-to-expiration settlement prices of the ethanol and corn contracts on the Chicago Mercantile Exchange and the RBOB gasoline and natural gas contracts on NYMEX from July 30, 2006, to September 8, 2010, archived at barchart.com. As each nearby contract comes to maturity, the series is rolled forward to the daily settlement price of the next closest contract. A similar procedure is used to construct a series of prices that are one year to maturity.

Storage, Long-Run Equilibrium, and the Spot Futures Price Relationship

The foregoing theory is only applicable to expectations about corn prices in the future. In the short run, the ethanol industry cannot quickly expand or contract to take advantage of disparities in corn and ethanol prices. This is true because there is a time lag involved in

constructing an ethanol plant and because it can take several months to enter bankruptcy. Thus, there is no reason to expect a relationship between corn and ethanol spot prices on the grounds that were proposed by de Gorter and Just (2008) and by Tokgoz et al. (2008).

However, corn, ethanol, and natural gas are storable commodities. As such, their spot prices, futures prices of differing maturities, and returns to storage are jointly determined by equilibrium in the spot and expected future spot markets as described in Peck (1985) and Tomek (1997). We illustrate this in Figure 2 by showing the ethanol, corn, and natural gas markets in two time periods called period one and period two. The period one prices are denoted p_1^i and represent spot prices. The period two prices are denoted $F_{1,2}^i$ and represent the futures price in period one for period two delivery. The long-run no-profit condition in the three markets is illustrated by showing the price of corn and natural gas as arguments in the expected period two ethanol supply curve, and by showing the price of ethanol in the expected period two demand curves for corn and natural gas. Also, the supply of each commodity in both periods depends on the level of inventory, I , which is carried between time periods. These inventories are the link between prices in period one and period two. The equilibrium carry in the market, that is, the difference between the future price and the spot price, must include compensation for physical costs of storage, interest, and convenience yield. In other words, we can write

$$(4) \quad F_{t,T} = p_t + carry_t * (T - t)$$

so that the price of a futures contract on a storable commodity, $F_{t,T}$, expiring at time T is equal to the current spot price, p_t , plus an equilibrium cost of carry, the size of which depends on the time to maturity. For example, if the spot price of corn on March 1 is

\$4.00/bu and there is a carry of \$0.03/bu per month prevailing in the market, then $F_{t,T} = \$4.00 + \$0.03*2 = \$4.06/\text{bu}$ is the price of the May corn contract. Notice that there is a degree of freedom in this equilibrium relationship. That is, equilibrium is defined by any two of the spot price, futures price, and return to storage. Therefore, we can form a forecast of spot prices by using the long-run no-profit condition, and an estimate of the return to storage prevailing in the corn market; that is,

$$(5) \quad p_t = F_{t,T} - \text{carry}_t * (T - t).$$

Discounted Expected Break-Even Corn Prices

These two conditions, a no-profit condition imposed on expected future prices and the storage arbitrage condition, suggest a simple model of how nearby corn futures prices behave. Given the price of ethanol and natural gas contracts maturing at some time in the future, T , there is one corn price that will satisfy the break-even relationship. This is the expected break-even energy value, $p_{t,T}^{c,EBEV}$, in equation (3). Further, since corn is storable, this long-run phenomenon is translated into the nearby price by discounting the *EBEV* of corn by the cost of storing corn from now until T . This means the nearby or spot price of corn should be approximated by

$$(6) \quad p_t^{c,DEBEV} = p_{t,T}^{c,EBEV} - \text{carry}_t * (T - t),$$

where *DEBEV* is short for discounted expected break-even energy value. Typically we would estimate the carry offered by the market as the price spread between the distant and nearby futures prices, $\text{carry}_t = F_{t,T}^c - F_{t,t}^c$, but we want to forecast the nearby price of

corn at date t so we cannot use this price in calculating our estimate of the carry. We use instead the average of the carry in the market on the previous five days.

If one uses spot ethanol and natural gas prices to forecast spot corn prices, the direction of bias is predictable and is based on the carry offered in the ethanol and natural gas markets relative to the carry in the corn market on a per gallon basis. Consider again the no-profit condition (1) written in terms of futures prices:

$$F_{t,T}^E = F_{t,T}^C \left(1 - \frac{17}{56} * 0.91\right) / 2.8 + F_{t,T}^{NG} + VC_{-corn} + FC .$$

Now if we write the futures prices instead as spot prices and returns to storage we have

$$p_t^E + carry_t^E = (p_t^C + carry_t^C) * 0.145 + (p_t^{NG} + carry_t^{NG}) + VC_{-corn} + FC ,$$

and rearranging so that the price of corn is on the left-hand side and so that the returns to storage are grouped together in the square brackets, we have

$$p_t^C = 6.897(-p_t^E + p_t^{NG} + VC_{-corn} + FC) + [6.897(-carry_t^E + carry_t^{NG}) + carry_t^C] .$$

Thus, a forecast based on spot prices will be biased because it does not account for the term contained in the square brackets. The direction of bias depends on the relative size of carry in the corn market and ethanol and natural gas markets. For example, suppose that the per bushel carry in the ethanol and natural gas markets are equivalent, i.e.,

$$6.897(-carry_t^E + carry_t^{NG}) = 0 , \text{ and that the per bushel carry in the corn market is}$$

$carry_t^C = \$0.25$. Then a forecast based on breakeven in the spot market would be biased downward by \$0.25, whereas our model adjusts for the relative magnitudes of the return to storage in each market. Another way to articulate this is that using spot ethanol and natural gas prices to forecast corn spot prices incorrectly discounts by the return to

storage in the ethanol and natural gas markets when the discounting actually should be done using the return to storage in the corn market.

To illustrate the performance of the proposed simple relationship as a forecast, we use the one-year-to-maturity ethanol and natural gas prices and equation (2) to construct a forecasted corn spot price, $p_t^{c,DEBEV}$. Then we compare this modeled price series with actual nearby corn futures prices, p_t^c and graph them in figure 3. Our model (blue line) is calculated as previously described and uses as the discount factor a moving average of the previous five days' implied return to storage. We define the corn market's implied return to storage as $F_{t,1Yr Maturity}^{corn} - F_{t,nearby}^{corn}$. Prior to the third quarter of 2006 this relationship clearly does not hold, but from approximately the beginning of 2007 to the time of this writing, the simple model has mimicked actual nearby corn prices well; it slightly overestimates the actual spot price of corn by \$0.04 per bushel during this time period. Comparison of the two price series suggests that traders were behaving as we described and that they did so when ethanol production was expanding in 2006 and 2007 and later when market conditions deteriorated in the second half of 2008 through the first half of 2009 and several ethanol companies entered bankruptcy.⁵

To contrast the improvement gained by using energy futures prices to capture the link between corn and ethanol prices, we use the same logic but use spot ethanol and natural gas prices instead. This means using equation (2) with spot prices, or

$$p_t^{c,BEV} = 2.8 \left[p_t^{eth} - p_t^{ng} - C_{-corn} \right] / \left[\left(1 - \frac{17}{56} * 0.91 \right) \right], \text{ with no need to discount by the}$$

implied carry. In figure 4 we graph actual nearby corn prices, p_t^c , and forecasted corn prices, $p_t^{c,BEV}$. This shows that using a break-even corn price derived from nearby ethanol

and natural gas prices as a model for corn spot prices overestimates the spot price of corn by \$0.86 per bushel on average, and the variance in the forecast error is approximately twice as large using the nearby price series as when the one-year-to-maturity series is used. This is consistent with the hypothesis that a long-run no-profit condition is maintained in the forward market. Using spot ethanol and natural gas prices biases the forecasted spot corn price and adds additional noise. The bias is due to the large backwardation in the ethanol market and contango in the natural gas market dominating the smaller contango in the corn market that prevailed over much of the sample.⁶ Also, the return to storage in the ethanol market was much more variable than the return to storage in the corn market, causing increased variance in the forecast errors relative to the forecast using one-year-to-maturity prices. Figure 5 shows the return to storage (carry) in the ethanol, corn, and natural gas markets for reference ($carry = F_{t,1YrMaturity}^{corn} - F_{t,nearby}^{corn}$).

Next, in figure 6, we compare the performance of the same model but use one-year-to-maturity gasoline futures prices instead of one-year-to-maturity ethanol futures prices. Since gasoline is a highly liquid market and the volume in the ethanol market is quite low, one might expect gasoline to be a better predictor of the price of corn in this type of model. Using this strategy calls for performing the exact same analysis but replacing $F_{t,T}^{eth}$ with $F_{t,T}^{gas}$ in equation (3). This shows that using gasoline can generally match the direction of the corn price trend, but the performance is inferior to that using ethanol prices. This can be explained by the fact that there are several additional factors in the petroleum markets that affect the entire forward curve of gasoline prices. These include world demand for petroleum products with a low price elasticity, time delays in production in response to demand shocks, geological limitations on increasing

production, and non-competitive pricing behavior of OPEC and domestic gasoline retailers or blenders (Borenstein, Cameron, and Gilbert 1997; Hamilton 2009).

Figure 7 shows the forecast errors of nearby and one-year-to-maturity ethanol and natural gas models compared to actual nearby corn prices; that is, figure 7 plots

$p_t^c - p_t^{c,DEBEV}$ and $p_t^c - p_t^{c,BEV}$ or the actual nearby corn futures prices minus our modeled discounted expected break-even energy value prices. As previously discussed, using spot ethanol and natural gas prices generally gives a modeled price that is sharply biased upward compared to actual nearby corn prices (see table 1).

Comparing the forecast errors depicted in figure 7 with the implied carry in figure 5, it is clear that the additional error in the forecast using nearby prices is mainly due to the carry in the ethanol market over the sample period. The carry in the corn and natural gas markets is relatively stable over the sample considered, and the difference between the one-year-to-maturity forecast error and the nearby forecast error tracks the carry in the ethanol market.

Time Series Tests

The models just described are admittedly simple. They assume that prices *should* be governed by the structural parameters defining a no-profit condition in the ethanol production market and then should proceed to predict corn prices based on these assumptions. First of all, the previous analysis implies that the price dynamics are such that the system immediately realigns with the no-profit equilibrium after experiencing a shock. In reality it is more likely that there are dynamics that describe this transition back to equilibrium. Further, by putting corn on the left-hand side, we assumed that ethanol

and natural gas prices determine corn prices, but it is possible that the causality actually goes the other way. In fact, it seems most reasonable that the direction of causality should depend on whether or not the Renewable Fuel Standard mandates are binding. For example, when ethanol mandates are not binding, the ethanol market can adjust to bring markets into equilibrium when an exogenous shock arrives. This is in contrast to the situation when ethanol mandates are binding. Under a binding mandate, ethanol production must remain fixed. If an exogenous shock arrives on the demand side, we should not observe a price response in the ethanol market. This means that during periods when the mandate is not binding, we will be more likely to observe ethanol prices responding to market shocks.

In the parlance of time-series analysis, our theory suggests that the long-run break-even condition in the ethanol market requires that the price of ethanol, natural gas, and corn be cointegrated. Non-stationary time series are said to be cointegrated if there exists at least one linear combination of the variables that is itself stationary (Granger 1981; Engle and Granger 1987; Granger and Weiss 2001). Non-stationary price series that are cointegrated can be fitted to a vector error correction model (VECM) to account for the long-run equilibrium relationship. This approach has some appeal over the approach used in the preceding analysis because the system is symmetric and thus allows one to estimate the nature of the price system without assuming structural relationships. Then, we can test to see if the estimated equilibrium relationship is consistent with the no-profit equation we posit in the preceding analysis. To perform this estimation we use the nearby and one-year-to-maturity data constructed for the analysis in the previous

section. The data series contains $T = 932$ daily observations from January 3, 2007, to September 8, 2010.

We select a lag length of $k = 3$ in the nearby series and a lag length of $k = 1$ in the one-year-to-maturity series based on the Sims (1980) likelihood ratio statistic, the final prediction error (FPE), the Akaike information criterion (AIC), the Hannan and Quinn information criterion (HQIC), and the Schwartz Bayesian information criterion (SBIC). We perform standard stationarity tests on the nearby and one-year-to-maturity ethanol, corn, natural gas, and RBOB gasoline series. The Dickey-Fuller $Z(t)$, Phillips-Perron $Z(\rho)$ and $Z(t)$ all fail to reject the null hypothesis of a unit root in each individual data series (Phillips 1987; Phillips and Perron 1988; Elliott, Rothenberg, and Stock 1996; Perron and Ng 1996). So we conclude that the corn, ethanol price, and natural gas price series are non-stationary.

Error Correction Model Results

Table 2 contains the results of Johansen's trace and maximal eigenvalue tests of cointegration (Johansen and Juselius 1990; Johansen 1991). We perform the tests on four sets of variables: (1) nearby ethanol, natural gas, and corn prices; (2) one-year-to-maturity ethanol, natural gas, and corn prices; (3) nearby gasoline, natural gas, and corn prices; and (4) one-year-to-maturity gasoline, natural gas, and corn prices. These are parallel to the cases we considered in the no-profit forecasting models developed earlier. The Johansen cointegration tests suggest that there is one cointegrating relationship between ethanol, natural gas, and corn both in the nearby and the one-year-to maturity series, but the null hypothesis of no cointegration could not be rejected using gasoline

prices. This is consistent with the earlier results, which showed that the actual realized nearby corn price generally moves with the breakeven corn price regardless of whether it was generated from nearby or one-year-to-maturity prices. Also, using gasoline prices in the breakeven relationship is not very useful, as the cointegration test reinforces.

Therefore, in the remainder of the analysis we no longer consider gasoline prices.

Next, we fit the ethanol, natural gas, and corn prices series to a vector error correction model (VECM) of the form

$$(7) \quad \Delta y_t = \alpha \beta' y_{t-1} + \sum_{i=1}^{k-1} \Phi_i \Delta y_{t-i} + \mu_t + \varepsilon_t \quad \text{for } t = 1, \dots, T,$$

where y_t is a vector of the time t prices, α is an $n \times 1$ vector of speed of adjustment coefficients, β' is a $1 \times n$ vector of cointegrating vectors, the Φ_i are $n \times n$ matrices, μ_t is a vector of intercept terms, and ε_t is a vector of iid random disturbances. The results of the VECM give us insight into the nature of the equilibrium relationship proposed in the previous section and detected by the Johansen tests. For example, the Johansen tests indicate that ethanol, natural gas, and corn are all cointegrated in both the nearby and in the one-year-to-maturity series; further examining the error correction vector can help us determine which data, nearby or one-year-to maturity, are more useful in explaining a no-profit relationship among ethanol, natural gas, and corn.

Table 3 contains the estimates of the VECM using nearby ethanol, corn, and natural gas prices while table 4 contains estimates of the VECM using the one-year-to-maturity prices. The estimation procedure was conducted in STATA 11. The estimated cointegrating vector is at the top of the table; the coefficient on ethanol has been normalized to 1. In the VECM using nearby prices, corn price is only marginally significant in the cointegrating relationship with a p-value of 0.07 but natural gas is

significant in the cointegrating relationship with a p-value of 0.00. If we contrast this with the estimated cointegrating vector using the one-year-to-maturity prices, we see that both corn and natural gas prices are significant in the cointegrating relationship with p-values of 0.00 and 0.05, respectively.

If we interpret the estimated cointegrating relationship as a breakeven or no-profit condition, then the estimated error correction vector, β , should reflect the technical production parameters: the β parameter on natural gas price should reflect the amount of natural gas required to produce one gallon of ethanol, and the β parameter on corn price should reflect the amount of corn (net of distillers grains) required to produce one gallon of ethanol. This raises a central question in our analysis. Is the estimated cointegrating vector from the VECM statistically indistinguishable from the breakeven vector derived from equations (2) and (3)? While the estimated coefficients in the cointegrating relationship are unidentified up to a constant, we normalize the estimated cointegrating relationship so that the coefficient on ethanol is equal to 1 and then compare to the breakeven vector implied by the earlier structural analysis. Equations (2) and (3) imply that the breakeven vector predicted by theory is

$$\left[\beta_{ethanol} \quad \beta_{natural\ gas} \quad \beta_{corn} \quad \beta_{constant} \right] = [1 \quad -0.008 \quad -0.253 \quad -0.114].$$

Tables 3 and 4 include the 95% and 99% confidence intervals on the parameter estimates of the cointegrating vector. The estimated parameter values of the cointegrating relationship are more consistent with the no-profit parameters in the one-year-to-maturity price system than in the nearby price system. In the one-year-to-maturity series, the breakeven parameter on corn price and natural gas price in the equilibrium relationship both fall within the 95% confidence intervals of the estimated parameters. Contrasting

this with the results from the nearby price series, the parameter on corn price in the equilibrium relationship is in the 95% confidence interval of estimated parameter; however, the parameter on natural gas price in the equilibrium relationship is in neither the 95% nor the 99% confidence interval on the estimated parameter. Also, the point estimate on the constant term in the one-year-to-maturity relationship is closer to the constant term in the breakeven relationship (-0.48 in the one year to maturity verses -0.70 in the nearby estimated relationship).

Considering the speed of mean reversion parameters, α , in each price equation in both the nearby and one-year-to-maturity price systems we can see how the price equations respond to shocks in the system. In the nearby price series, the cointegrating relationship is significant in the ethanol and natural gas equation but only marginally significant in corn with p-values of 0.01, 0.04, and 0.08, respectively. The equilibrium relationship is not significant in the corn price equation at the 5% level, and further, the sign of the speed-of-reversion parameters is the same in the ethanol and corn price equations. If this estimated equilibrium relationship were driven by a no-profit condition, then the speed-of-reversion parameters should be of opposite signs in the ethanol and corn price equations. This would reflect a situation in which positive profits cause ethanol prices to fall and corn prices to rise until no profits remain. Therefore, the estimated relationship in the nearby price series either does not reflect a no-profit relationship, or if it does the coefficient on the equilibrium relationship in the corn equation is statistically indistinguishable from zero.

In the one-year-to-maturity VECM, the cointegrating relationship is only significant in the ethanol price equation, indicating that when the system experiences a

shock, it is predominantly the ethanol price that adjusts to bring the price relationship back into long-run equilibrium. With a point estimate of -0.044 this means that if the equilibrium relationship is disturbed by +\$0.10, i.e., a \$0.10 per gallon profit in corn-based ethanol production can be locked in the futures markets, then the price of ethanol will decrease by about half a penny per gallon per day until the equilibrium relationship is established again. This is consistent with our expectations for the price system during periods when the Renewable Fuel Standard mandate is not binding.⁷ However, the result that ethanol is the price that responds to bring the three back into equilibrium is in contrast to the implicit assumption in the theoretical economic literature that crude prices cause gasoline prices, which cause ethanol prices, which cause corn prices. The quantitative interpretation of the VECM does not change when the model is run for different lag length specifications, and therefore we do not report a full battery of robustness checks here.

The results of the cointegration analysis lend support for the case that corn, ethanol, and natural gas prices are in fact governed by a breakeven relationship. Further, we conclude that the empirical results are supportive of the hypothesis that the breakeven relationship is maintained not in the spot market but rather in the forward markets for ethanol, natural gas, and corn.

Summary and Conclusions

This article used the theories of market efficiency and supply of storage to develop a conceptual link between the corn and ethanol markets and explored statistical evidence for the link. Unlike previous studies, we proposed that the link between the corn and the energy sectors is manifest in *futures* prices at least one year to maturity. This is because

the link between corn and ethanol prices should come about from a long-run no-profit condition; therefore, the link is established in forward prices. Then cost-of-carry arbitrage conditions that are specific to the corn, ethanol, and natural gas futures markets are used to calculate a spot corn price forecast from the long-run relationship.

We concluded that there is a clear link between ethanol and corn prices. This relationship began in mid-2006 and it has continued to at least the fall of 2010. This relationship appears to be sufficiently strong to dominate all other forces at play in setting the relationship between corn and ethanol prices in recent years. For example, our forecast model that relied on only a long-run breakeven condition had a forecast error of \$0.04 and a standard deviation of \$0.35. Using a breakeven forecast model with spot prices yields a forecast error of \$0.86 and a standard deviation of \$0.74.

The relative slopes of the forward curves specific to the corn, ethanol, and natural gas futures markets govern the relationships between the long-run condition and spot prices. Over the period of ethanol expansion, the ethanol market has almost always been in backwardation and the natural gas market has predominately been in contango. This situation is consistent with the spot-based breakeven corn price being biased upwards.

We performed cointegration analyses to econometrically test our hypothesis. These tests lend support for the case that corn, ethanol, and natural gas prices are in fact governed by a breakeven relationship. Further, these tests indicated that the breakeven relationship is maintained not in the spot market but rather in the futures markets for ethanol, natural gas, and corn one year to maturity.

To the extent that ethanol prices respond to events in the traditional energy markets, this link has profound impacts on the agricultural sector. Farm policy now must

be written with an understanding of how feedback between agricultural policy and the energy sector affect all players in the economy. The traditional income-smoothing policies of U.S. farm policies have become largely irrelevant in the presence of a large ethanol sector. This means the nature of risk farmers face has changed. Programs designed to help farmers mitigate risk should be reassessed to take the new market conditions into account. Further, price forecasting and outlook tools must be revamped to include an incorporation of the link between the energy and crop markets.

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Endnotes

¹ Supply and use statistics can be found in the USDA Economic Research Service Feed Grain Database <http://www.ers.usda.gov/data/feedgrains/FeedYearbook.aspx>

² Corn and ethanol prices are from the USDA Agricultural Marketing Service, which can be accessed in the Market News area of the AMS website:

<http://www.ams.usda.gov/AMSV1.0/> .

³ The cost estimates are consistent with those calculated from the Monthly Profitability of Ethanol Production calculator available on the Ag Decision Maker website at Iowa State University (<http://www.extension.iastate.edu/agdm/>), with 6% cost of capital.

⁴ The Ag Market News Reports can be accessed in the Bioenergy section of the AMS website: <http://www.ams.usda.gov/AMSV1.0/LSMarketNews>.

⁵ Some news headlines from various points in time throughout our sample period illustrate this point: (1) “Shares of VeraSun, Ethanol Producer Surge After IPO,” *Bloomberg*, June 14, 2006; (2) “Ethanol Start-Ups and the Bankruptcy Bogeyman,” *Ethanol Producer Magazine*, March 2008; (3) “Ethanol Bankruptcies Continue,” *Energy Tribune*, February 4, 2009; (4) “ADM Tops Wall Street View, Shares up 4 Percent,” Reuters, February 2, 2010.

⁶ A market is said to be in contango when the contracts closer to maturity have a lower price than contracts that are farther to maturity. Conversely, a market is said to be in backwardation when the close-to-maturity contracts have a price higher than the contracts that are farther to maturity.

⁷ Renewable Fuel Standard mandates have almost never been binding during the timeframe of this analysis.

Table 1. Forecast Errors of the Breakeven and Discounted Breakeven Corn Price Model Using Nearby and One-Year-Forward Ethanol, Natural Gas, and Corn Prices, Respectively

Data Series	Energy Price Based on:	Forecast Error Mean	Forecast Error Standard Deviation
Nearby	Ethanol	-\$0.86	\$0.74
1 Yr Forward	Ethanol	-\$0.04	\$0.35
1 Yr Forward	RBOB Gasoline	-\$1.41	\$1.20

Table 2. Johansen Cointegration Tests

			Trace test	5% c.v.	1% c.v	Max test	5% c.v.	1% c.v
Nearby	Ethanol, Natural Gas & Corn	$r \leq 0$	31.51*	29.68	35.65	16.56	20.97	25.52
		$r \leq 1$	14.94	15.41	20.04	14.41	14.07	18.63
		$r \leq 2$	0.52	3.76	6.65	0.52	3.76	6.65
Nearby	Gasoline, Natural Gas & Corn		16.96	29.68	35.65	11.23	29.68	35.65
			5.73	15.41	20.04	4.85	15.41	20.04
			0.88	3.76	6.65	0.88	3.76	6.65
1 Year Forward	Ethanol, Natural Gas & Corn	$r \leq 0$	30.98*	29.68	35.65	24.33*	20.97	25.52
		$r \leq 1$	6.65	15.41	20.04	5.69	14.07	18.63
		$r \leq 2$	0.96	3.76	6.65	0.96	3.76	6.65
1 Year Forward	Gasoline, Natural Gas & Corn	$r \leq 0$	14.72	29.68	35.65	9.06	20.97	25.52
		$r \leq 1$	5.65	15.41	20.04	4.59	14.07	18.63
		$r \leq 2$	1.06	3.76	6.65	1.06	3.76	6.65

Notes: Data tested are from January 3, 2007 to September 8, 2010.

Constant term included in the cointegrating vector.

Table 3. Error Correction Results and Granger Causality, Nearby Price Series

$$\Delta y_t = \alpha\beta' y_{t-1} + \sum_{i=1}^{k-1} \Phi_i \Delta y_{t-i} + \mu_t + \varepsilon_t$$

	<i>Constant</i>	<i>Ethanol</i>	<i>Natural Gas</i>	<i>Corn</i>
Error correction vector β	-0.70	1	-3.34	-.124
<i>p</i> -value	N/A	N/A	0.00	0.07
95% Confidence Interval	N/A	N/A	(-5.101, -1.574)	(-0.260, 0.010)
99% Confidence Interval	N/A	N/A	(-5.656, -1.019)	(-0.300, 0.052)

	Variable	Coefficient	t-statistic	<i>p</i> -value
Ethanol	α_1	-0.031	-2.83	0.01
	Ethanol lag1	0.010	0.42	0.67
	Ethanol lag2	-0.084	-3.73	0.00
	Natural Gas lag1	-0.094	-0.34	0.73
	Natural Gas lag2	-0.882	-3.23	0.00
	Corn lag1	-0.008	-0.82	0.41
	Corn lag2	0.322	33.85	0.00
	Constant	0.000	0.17	0.87
Natural Gas	α_2	0.003	2.03	0.04
	Ethanol lag1	-0.001	-0.43	0.67
	Ethanol lag2	-0.001	0.40	0.69
	Natural Gas lag1	-0.063	-1.90	0.06
	Natural Gas lag2	0.027	0.82	0.41
	Corn lag1	0.001	1.02	0.31
	Corn lag2	0.000	0.37	0.71
	Constant	-0.000	-1.03	0.30
Corn	α_3	-0.068	-1.75	0.08
	Ethanol lag1	0.019	0.24	0.81
	Ethanol lag2	0.004	0.05	0.96
	Natural Gas lag1	0.159	0.16	0.87
	Natural Gas lag2	0.028	0.03	0.98
	Corn lag1	-0.003	-0.09	0.93
	Corn lag2	-0.025	-0.75	0.46
	Constant	-0.000	-0.02	0.98

Note: Nobs = 932, January 3, 2007 to September 8, 2010

Table 4. Error Correction Results and Granger Causality, One-Year-Forward Price Series

$$\Delta y_t = \alpha\beta' y_{t-1} + \sum_{i=1}^{k-1} \Phi_i \Delta y_{t-i} + \mu_t + \varepsilon_t$$

	<i>Constant</i>	<i>Ethanol</i>	<i>Natural Gas</i>	<i>Corn</i>
Error correction vector β	-0.48	1	-0.86	-0.26
<i>p</i> -value	N/A	N/A	0.05	0.00
95% Confidence Interval	N/A	N/A	(-1.71, -0.004)	(-0.30, -0.21)
99% Confidence Interval	N/A	N/A	(-1.98, 0.26)	(-0.32, -0.20)

	Variable	Coefficient	t-statistic	<i>p</i> -value
Ethanol	α_1	-0.044	-3.23	0.00
	Ethanol lag1	-0.056	-1.22	0.22
	Natural Gas lag1	0.158	0.69	0.49
	Corn lag1	0.035	2.37	0.02
	Constant	0.000	0.08	0.94
Natural Gas	α_2	-0.000	-0.11	0.91
	Ethanol lag1	-0.008	-1.10	0.27
	Natural Gas lag1	-0.040	-1.16	0.25
	Corn lag1	0.006	2.47	0.01
	Constant	-0.000	-0.92	0.36
Corn	α_3	0.004	0.09	0.93
	Ethanol lag1	0.083	0.60	0.55
	Natural Gas lag1	0.015	0.02	0.98
	Corn lag1	0.034	0.75	0.46
	Constant	0.000	0.30	0.76

Note: Nobs = 932, January 3, 2007 to September 8, 2010

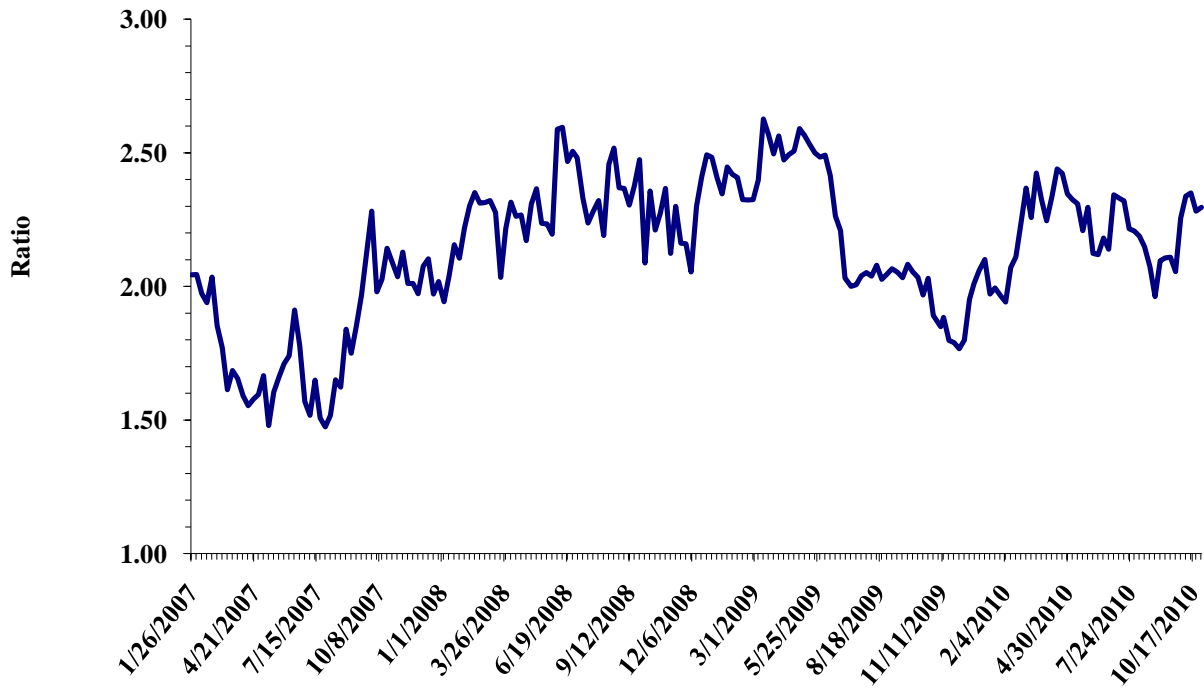


Figure 1. Ratio of corn to ethanol price at Iowa plants, 01/26/07 - 10/29/10

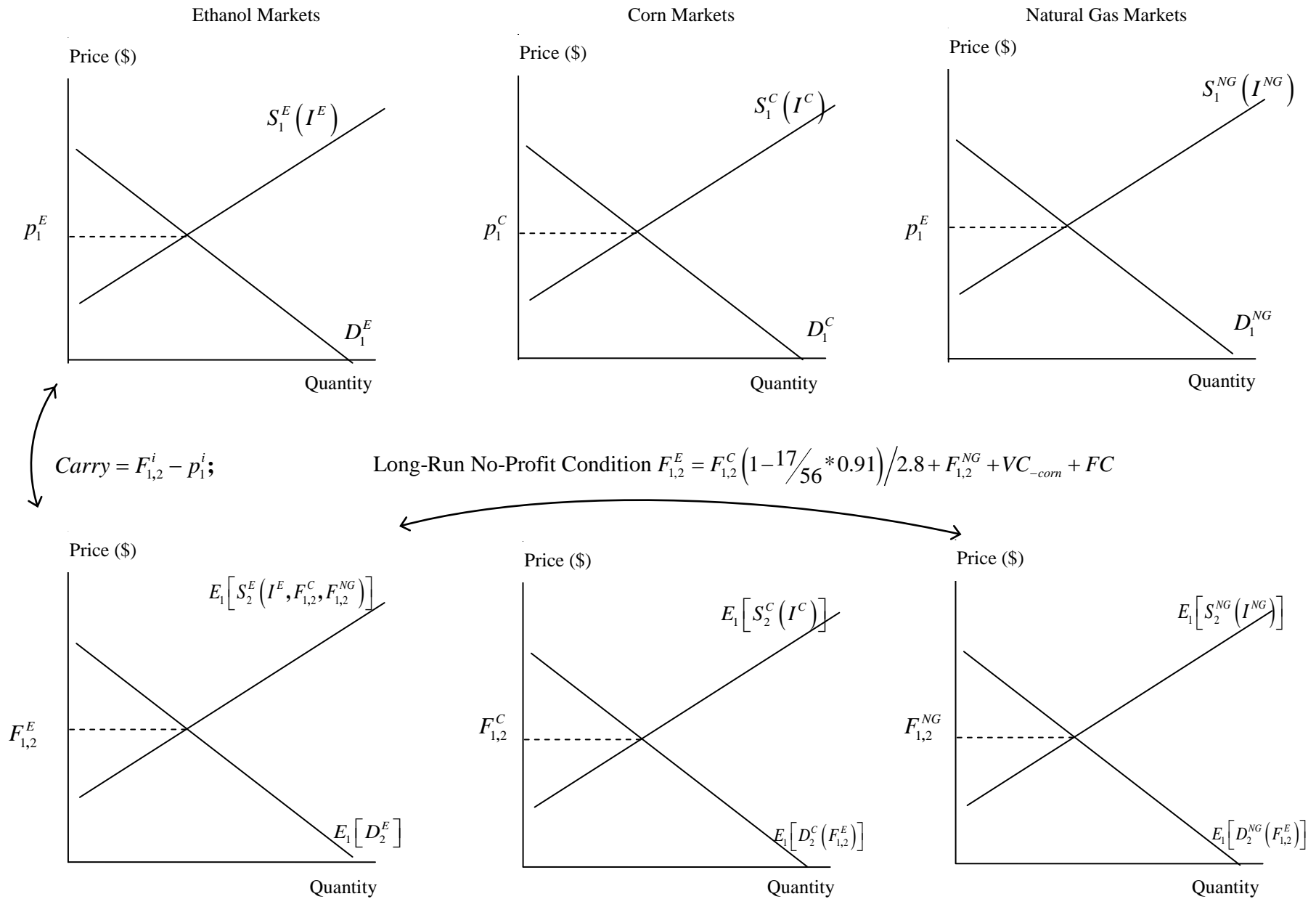


Figure 2: A Multimarket, Intertemporal Equilibrium Transmits the Long-Run No-Profit Condition to the Spot Market

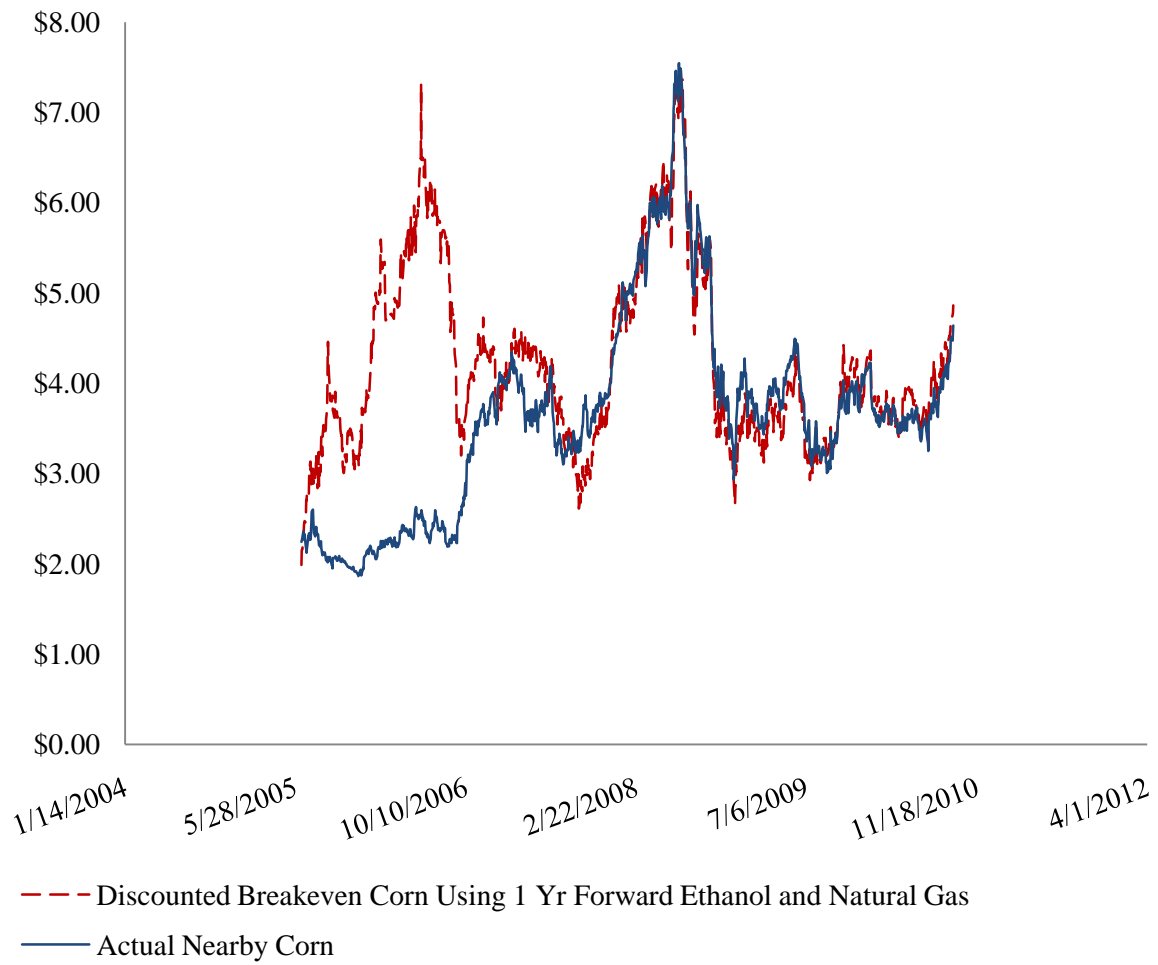


Figure 3. Corn Price Forecast from One-Year-Forward Break-Even Rule, January 3, 2007, to September 8, 2010

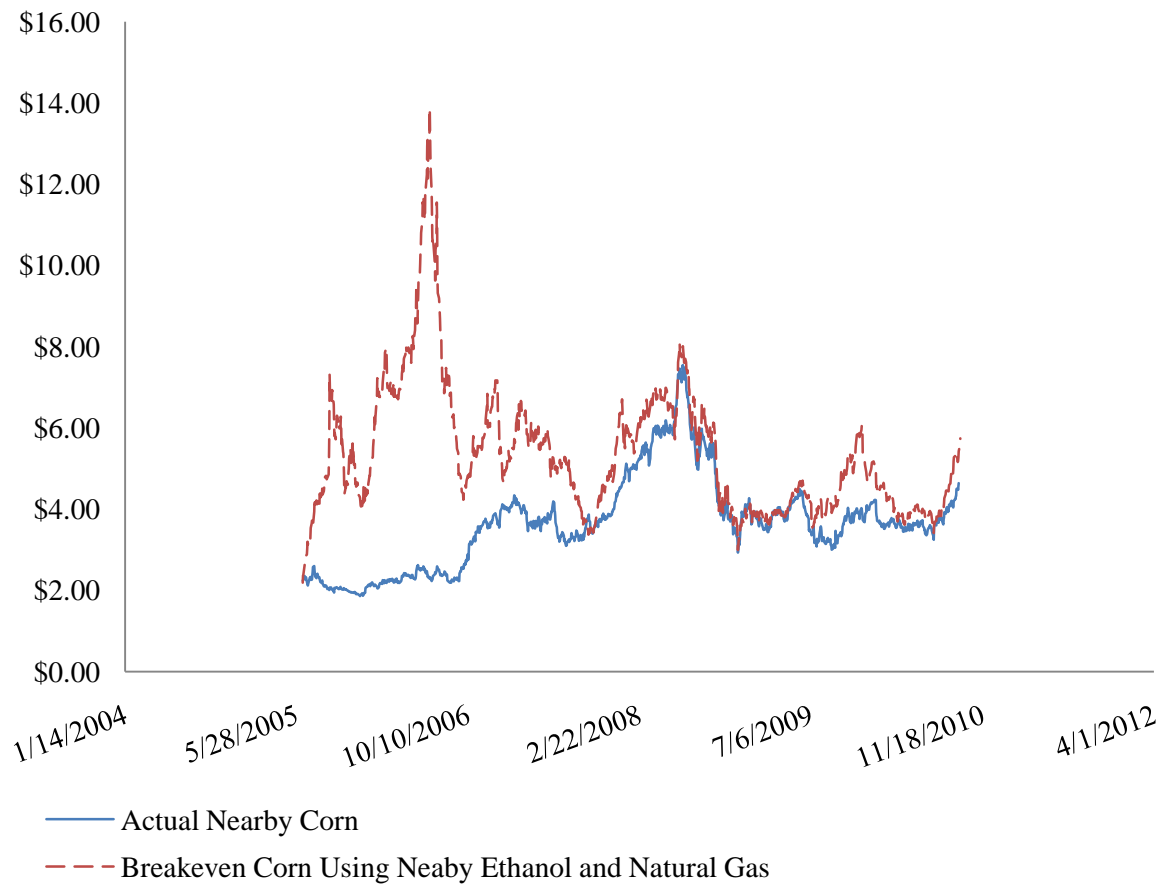


Figure 4. Corn Price Forecast from Nearby Break-Even Rule, January 3, 2007, to September 8, 2010

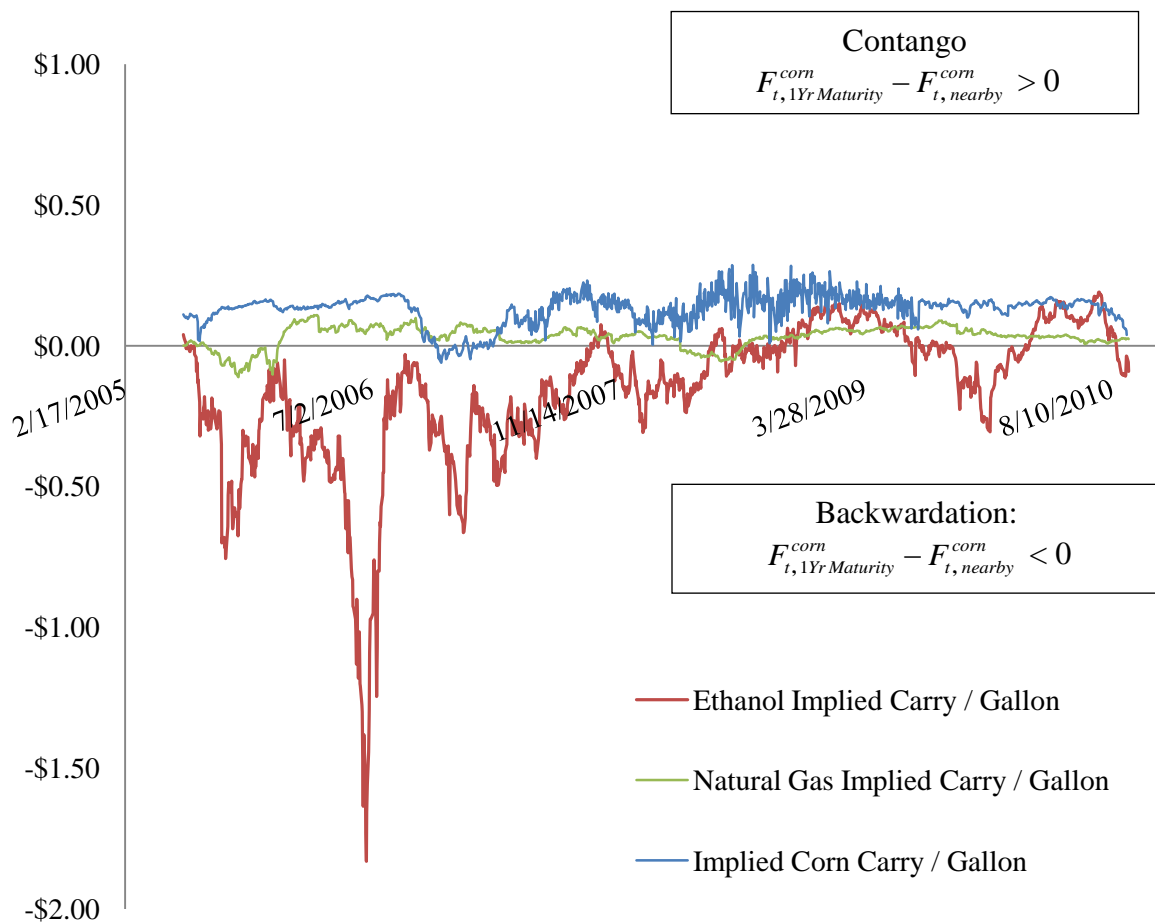


Figure 5. Market's Implied Carry for Storing One Year in the Ethanol, Natural Gas, and Corn Markets, January 3, 2007, to September 8, 2010

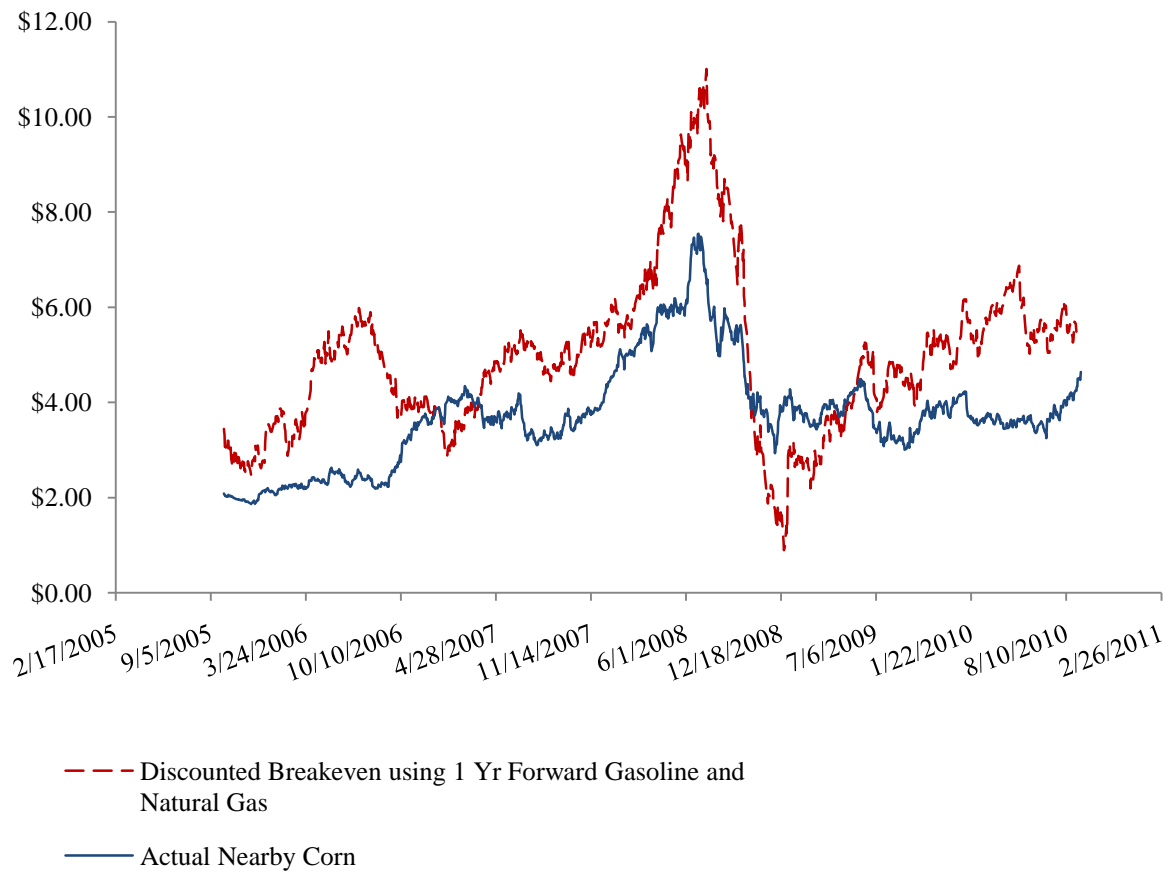


Figure 6. Corn Price Forecast from One-Year-Forward Break-Even Rule and Gasoline Prices, January 3, 2007, to September 8, 2010

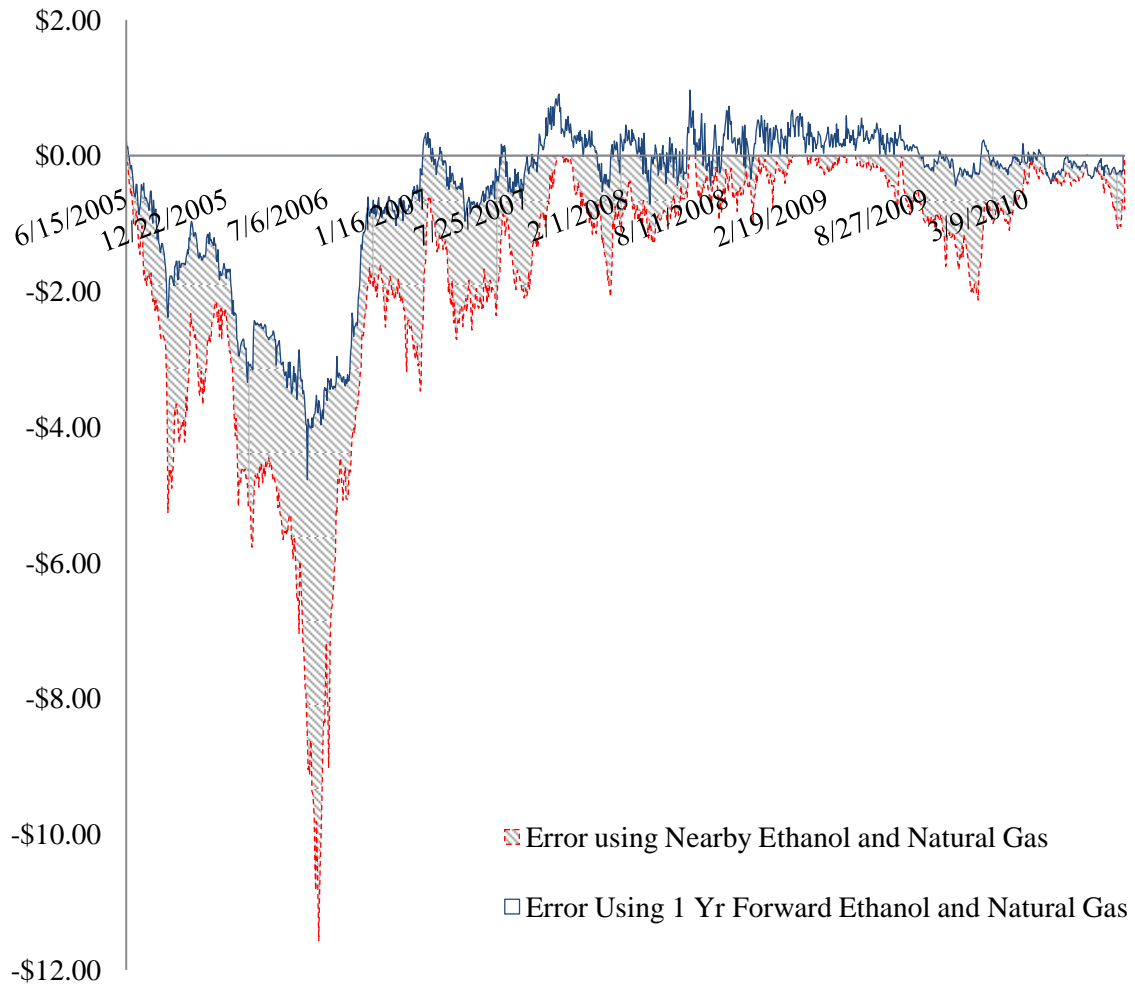


Figure 7. Forecast Errors of the Nearby and One-Year-Forward Models, January 3, 2007, to September 8, 2010