Using the Competitive Storage Model to Estimate the Impact of Ethanol and Fueling

Investment on Corn Prices^{*}

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Abstract

The impact of biofuel mandates on the prices of commodities used to produce food continues to be a major consideration by policy makers. More recently concern about high costs by oil companies from complying with mandates led to reductions in U.S. biofuel mandates. To gain insights into the policy impacts of mandates on agricultural commodity prices and compliance costs requires development of dynamic models that can capture the fact that many agricultural commodities used to produce biofuels can be stored and that flexible compliance mechanisms allow for banking and borrowing of tradable permits. US biofuel

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mandates are enforced using a system of tradable permits, called RINs. RIN market dynamics are important because RINs can be banked for the future or borrowed from the future. Corn is the primary U.S. biofuel feedstock and is storable. Rational expectations competitive storage models are best suited to capture the dynamic behavior of commodity markets. Such a model is developed here for corn and RIN markets to estimate the impacts of alternative future ethanol mandate levels. The model considers corn use for ethanol, storage and all other uses in each period, accounting for two random variables: oil prices and corn yields. Borrowing and banking provisions of the Renewable Fuels Standard mandate are explicitly integrated into the model. We use the model to provide estimates of the impact on corn prices, corn plantings and ethanol production under two ethanol mandate scenarios for six marketing years from 2016/17. Our scenarios are a combination of volume requirements and infrastructure investment. The first scenario is one in which corn ethanol mandates stay the same as required in the current and proposed RFS and additional E85 stations are introduced that allow for compliance with higher mandates. The second scenario is one in which no investment occurs and the Environmental Protection Agency reduces the mandate to 13.87 billion gallons, a level that can just be met with 10 percent ethanol blends. Comparing the results for two scenarios, we find that average corn prices are about 5 to 6 percent with the reduced mandates or about 22 to 30 cents per bushel, while average RIN prices drop from around 60 to 40 cents per RIN.

Key words: Ethanol Mandate; Corn Prices; RIN prices; Competitive Storage Model; Collocation Method

1 Introduction

The impact of increasing biofuel consumption has been the subject of intense study over the last few years because of concerns that policies that support biofuels may increase food prices (World Bank) and greenhouse gas emissions (Rajagopal and Plevin (2013)). However it was concern about high compliance costs that led the U.S. Environmental Protection Agency (EPA) to reduce mandate levels below those specified in the Renewable Fuel Standard (RFS). EPA reduced the volume of biofuel mandates that could be met with corn ethanol in 2014, 2015, and 2016 to 13.61, 14.05, and 14.5 billion gallons respectively from the original RFS levels of 14.4, 15.0 and 15.0 billion gallons. It is possible that high compliance costs could lead to increased fuel prices (CBO 2014) so EPA's actions could have been driven by concerns about higher consumer fuel costs rather than the direct cost of compliance.

Compliance with RFS mandates is demonstrated by fuel producers and importers acquiring sufficient Renewable Identification Numbers (RINs). RINs are produced when biofuels are produced. Their 38-digits facilitate traceability of each biofuel batch. Parties obligated under the RFS obtain RINs either by buying domestically produced biofuel, imported biofuel or by buying RINs in the market. Optimizing firms will choose to buy RINs if the price of RINs is less than their net cost of buying and blending biofuels that have the RINs attached. The net cost of buying and blending biofuels is the difference between the market price of the biofuel and its value in the fuel market. In theory, the price of RINs in the market will reflect this net cost. When RFS mandates push biofuel consumption beyond the level that market forces alone would support, then the price of RINs will increase. RIN prices will approach zero when mandates are lower than the quantity that market forces support. Thus RIN prices provide a market measure of the impact of the RFS on biofuel consumption and production as well as providing a measure of marginal compliance costs.

To lower the cost of complying with biofuel mandates the Environmental Protection Agency (EPA) allows RINs to be banked or borrowed. Thus the price of RINs not only reflect current net costs of buying and blending biofuels but also anticipated future net costs.

Rubin (1996) developed temporal arbitrage conditions for tradable environmental permits that can be banked or borrowed. McPhail (2010) applied these conditions to the RIN market and solved the optimal conditions for how many RINs to store based on no-arbitrage profit conditions. However, she ignored the 20% borrowing and banking constraints and, to simplify her model, assumed that ethanol mandates disappear in the near future. This assumption allowed her to more easily obtain two-year-ahead RIN price distributions. Others who have modeled the impacts of RFS mandates in a dynamic setting include Thompson, Meyer and Westhoff (2008, 2009a, 2009b). The model in these papers did not explicitly incorporate borrowing and banking of RINs. Thompson, Meyer and Westhoff (2011) modeled RIN banking as a decreasing function of the current RIN price. They generated a dynamic price path for RIN prices but storage in their model depended only on the current RIN price rather than expected future RIN prices. Thus the model cannot be characterized as a forward-looking rational expectations model.

Wright (2014), Hochman et al. (2012), Carter et al. (2008), and Mitchell (2008) showed the importance of grain storage in predicting the food price effect of biofuel mandates. Accounting for storage is important because storage buffers the price impacts of supply and demand shocks. Peterson and Tomek (2005) applied the rational expectations competitive storage model to the U.S corn market and used the collocation method to solve the unknown functional forms of expected price. Comparing the monthly simulated prices to the price behavior in the commodity market in 1990s, they concluded that the prices produced from this model can mimic complicated commodity price behavior.

Here we develop a competitive storage model of RINs and corn to analyze the impacts of biofuel mandates. To make our model tractable, we simplify our treatment of the RFS and model a mandate for corn-based ethanol. In reality, there is no mandate for corn ethanol per se; rather corn ethanol can be utilized to satisfy no more than a certain portion of the total RFS. In 2016, 14.5 billion corn ethanol RINs can be used to satisfy the 18.11 billion RINs needed for compliance. The remaining 3.61 billion RINs must come from non-corn domestic

or imported ethanol, or biomass-based diesel, or other qualifying biofuels. A more detailed treatment of the competition between biofuels to meet RFS mandates would capture the likely use of biomass-based diesel RINs to substitute for part of the corn ethanol mandate when ethanol mandates are difficult to meet. In this case the effect of our simplification is to overstate the impacts on corn and RIN prices from higher corn ethanol mandates.

The contribution of this paper is to demonstrate how the future impacts of RFS ethanol mandates can be estimated using a rational expectations competitive storage model. The impact of mandates are estimated by comparing model solutions under two scenarios. Each scenario is a combination of volume requirements and infrastructure investment. The first scenario assumes that EPA allows mandates to increase to 15 billion gallons, which is the cap on RFS mandates that can be met with corn ethanol. The second scenario assumes that EPA keeps mandates at levels that can be more easily met using ethanol consumed in 10% ethanol-gasoline blends, a policy that has been strongly supported by obligated parties.¹ Our competitive storage model of RINs and corn has two sources of uncertainty: corn yields and gasoline prices. The resulting stochastic dynamic programming model is solved through the 2021 crop year using USDA projections of corn demand along with trend yield adjustments. The solved model is used to simulate future corn and RIN price distributions that show the impact of increasing mandates. Results indicate that increasing mandates have rather modest impacts on future corn prices but large impacts on RIN price distributions.

2 The Model

Our model consists of perfectly competitive markets, an obligated party who produces gasoline under constant cost conditions and who blends ethanol and gasoline to make fuel, a representative profit-maximizing corn farmer with an upward sloping supply curve that depends on the expected future price of corn, and a representative biofuel producer who combines corn and other inputs to produce ethanol. Each year the farmer chooses acreage

¹The position of obligated parties is nicely illustrated in the discussion of the RFS that can be found at http://www.energytomorrow.org/blog/2013/11/22/magical-thinking-on-e85-and-ethanol-mand_pushed

based on next year's expected corn price. Harvested corn is consumed as either ethanol or other uses or put into storage. Storage levels are such that no temporal arbitrage profits are possible. The obligated gasoline producer/blender decides how much ethanol to buy each year and how many RINs to borrow or bank to minimize discounted lifetime costs of compliance with mandated ethanol volumes.²

The corn farmer bases current year's planting decisions on next year's post-harvest expected price as shown in equation (1). A_{t+1} is acreage harvested in $t+1$. $A(\cdot)$ is a concave function of $E_t(p_{ct+1})$, i.e., $A'(\cdot) > 0$ and $A''(\cdot) < 0$.

$$A_{t+1} = A(E_t(p_{ct+1})) \quad (1)$$

Equilibrium storage satisfies the following no-arbitrage condition

$$\beta E_t(p_{ct+1}) = p_{ct} + SC_t(x_{t+1}), \quad (2)$$

where x_{t+1} is beginning corn stock in time $t+1$ and per-bushel storage costs is denoted by SC_t . Storage cost includes convenience yield which goes to negative infinity when stock level approaches zero. The discount factor β equals $1/(1+r)$ where r is the interest rate. Equilibrium corn storage is where the expected gains from holding corn to the next period equals storage costs. The expected revenue from storing a bushel of corn is the discounted expected price of corn. The cost of storing one bushel of corn is the per bushel corn price at time t plus storage cost. If there is positive economic profit from holding corn, firms and

² As defined by RFS rules, obligated parties are any company that produces gasoline or diesel fuel within the 48 contiguous states or Hawaii, or any importer of gasoline or diesel fuel into the 48 contiguous states or Hawaii. Blenders, who buy ethanol and gasoline and blend ethanol into gasoline, are not obligated parties under the RFS. However, some blenders such as BP and ConocoPhillips, also own oil refineries and so are obligated parties. The mandate for each obligated party is determined as a percentage of the total gasoline they sell in the United States. We simplify by combining blenders and obligated parties into one entity.

individuals will store it. With more corn stored for $t+1$, total corn consumption decreases in t and total corn supply increases in $t+1$. The current corn price goes up and the expected corn price goes down. When expected gains from storage equal storage costs the incentive to store corn disappears and a no-arbitrage profit condition is reached. When stock level approaches zero, marginal storage cost goes to negative infinity. This specification of marginal storage cost eliminates stock-out conditions.

The non-ethanol demand for corn is denoted by $D_c(p_{ct})$, where p_{ct} is the corn price at time t . Corn demand by ethanol producers is a derived demand which depends on the US demand for ethanol. Ethanol demand includes both the demand for ethanol in E10 and ethanol in E85. Both demand curves are based on Pouliot and Babcock (2014) . Total U.S. ethanol disappears according to an ethanol usage curve $D_e(p_{et}^d, p_{gt})$, where p_{et}^d and p_{gt} are the ethanol price and exogenous gasoline price at which an amount $D_e(p_{et}^d, p_{gt})$ of ethanol is used. We assume that gasoline supply is perfectly elastic and that changes in the gasoline price shift the demand curve for ethanol. The model assumes that ethanol is only produced for the domestic market, although in reality the U.S. is both an exporter and an importer of ethanol. Exports and imports for the recent five years are reported in Table 1.³ To put the Table 1 trade flows into perspective, domestic ethanol consumption is expected to be about 14.5 billion gallons in 2016.

Table 1: U.S. Ethanol Exports and Imports from 2011 to 2015*

	2011	2012	2013	2014	2015
Exports	1193	732	617	836	836
Imports	196	555	400	84	93

*Unit is million gallons.

The gasoline sector is represented by a gasoline producer with costs that are proportionate to stochastic oil prices. The supply curve of gasoline is therefore perfectly elastic and stochastic. The gasoline producer is an obligated party who minimizes the lifetime cost

³Data is taken from <http://www.ethanolrfa.org/wp-content/uploads/2016/02/2015-US-Ethanol-Trade-Statistics-Summary.pdf>

of meeting ethanol mandates. The cost of meeting the mandate in each period is $c_t(e_t - \varepsilon_t)$, where e_t is total ethanol consumed in time t and ε_t is the amount of ethanol that would be consumed without a mandate. Thus $c_t(\cdot)$ measures compliance cost. The blender can borrow or bank RINs up to 20% of the next period's total mandate. RFS rules specify that RINs are valid for only two years and forbids RIN borrowing in consecutive years. To simplify model solutions we allow borrowing in consecutive years when economic incentives to do so exist. This simplification results in a small decrease in the marginal cost of meeting the mandate in some states of the world because the actual rules are more stringent than we assume. The simplification also likely decreases the number of banked RINs in some states of the world because it lowers the cost of not having adequate banked RINs when they are needed.

Let B_t be the beginning stock of RINs and M_t be the mandate in each period t . The obligated party minimizes lifetime compliance costs:

$$\min_{e_t, \forall t} \sum_{t=0}^{\infty} \beta^t E_0(c_t(e_t - \varepsilon_t)) \quad (3)$$

$$s.t. \quad B_{t+1} = \min(B_t + e_t - M_t, 0.2M_{t+1}) \quad (4)$$

$$B_t + e_t - M_t \geq -0.2M_{t+1} \quad (5)$$

where $0.2M_{t+1}$ is the upper bound of banked RINs and $-0.2M_{t+1}$ is the lower bound of borrowed RINs. Equation (4) says that the carryover B_{t+1} cannot exceed the maximum carryover allowed at time t . Available RINs stock is the sum of RIN stock and RINs generated less the mandate, $B_t + e_t - M_t$. If available RIN stock is not greater than the banking limit, $B_t + e_t - M_t$ will be banked. If available RIN stock exceeds the banking limit, only $0.2M_{t+1}$ can be used in the next period and the rest of the available RINs will expire. Borrowing constraint (5) says that carryover RIN stock should be greater than -0.2 of next period's mandate. RIN stock is a state variable in ethanol producer's problem.

Let

$$V_t(B_t, t) = \min_{e_t} c_t(e_t - \varepsilon_t) + \beta E_t V_{t+1}(\min(B_t + e_t - M_t, 0.2M_{t+1}), t+1) + \lambda_t(-0.2M_{t+1} - (B_t + e_t - M_t)), \quad (6)$$

where λ_t is Karush-Kuhn-Tucker (K.K.T) multiplier. The K.K.T. conditions are:

$$e_t : c'_t(e_t - \varepsilon_t) + \beta \frac{\partial E_t V_{t+1}(\min(B_t + e_t - M_t, 0.2M_{t+1}), t+1)}{\partial e_t} - \lambda_t \geq 0, \quad \frac{\partial V_t(B_t, t)}{\partial e_t} \cdot e_t = 0, \quad (7)$$

$$\lambda_t : -0.2M_{t+1} - (B_t + e_t - M_t) \leq 0, \quad (-0.2M_{t+1} - (B_t + e_t - M_t)) \cdot \lambda_t = 0, \quad \lambda_t \geq 0. \quad (8)$$

The envelope condition is

$$\frac{\partial V_t(B_t, t)}{\partial B_t} = \beta \frac{\partial E_t V_{t+1}(\min(B_t + e_t - M_t, 0.2M_{t+1}), t+1)}{\partial B_t} - \lambda_t. \quad (9)$$

Without RINs borrowing and banking, the ethanol producer has to produce at least the mandated level in each period. After introducing borrowing and banking provisions, the ethanol producer can produce less than or more than the mandated level to minimize the total cost of meeting the obligated volume for all time periods. Equation (7) means that if total ethanol production is not zero then $\partial V_t(B_t, t)/\partial e_t = 0$. Ethanol produced, e_t , cannot be zero because at least 80% of the mandate has to be met by RINs generated in this period. Thus the K.K.T condition with respect to e_t (7) becomes

$$e_t : c'_t(e_t - \varepsilon_t) + \beta \frac{\partial E_t V_{t+1}(\min(B_t + e_t - M_t, 0.2M_{t+1}), t+1)}{\partial e_t} - \lambda_t = 0. \quad (10)$$

If the borrowing and banking constraints are not binding, then marginal cost of the

borrowing constraint equals zero ($\lambda_t = 0$) and all available RINs will be banked $B_{t+1} = B_t + e_t - m_t$. Equation (10) becomes

$$c'_t(e_t - \varepsilon_t) = -\beta \frac{\partial E_t V_{t+1}(\min(B_t + e_t - M_t, 0.2M_{t+1}), t + 1)}{\partial e_t}, \quad (11)$$

and together with equation (9), we have the marginal compliance cost in time t equals the discounted expected marginal compliance cost in the next period:

$$c'_t(e_t - \varepsilon_t) = \beta E_t(c'_{t+1}(e_{t+1} - \varepsilon_{t+1})). \quad (12)$$

The relationship between marginal compliance cost in t and expected marginal compliance cost in $t + n$ can be derived from equation (12),

$$c'_t(e_t - \varepsilon_t) = \beta^n E_t(c'_{t+n}(e_{t+n} - \varepsilon_{t+n})). \quad (13)$$

Equation (13) says that the expected marginal compliance cost increases at the interest rate. If the expected marginal compliance cost increases at a rate greater than interest rate, the gasoline producer would have an incentive to bank RINs. With more ethanol produced and more RINs banked, current marginal compliance cost increases and expected marginal cost decreases. No more RINs will be banked until current marginal compliance cost equals the discounted expected marginal compliance cost. If the expected marginal compliance cost grows less than interest rate, ethanol producer will borrow RINs from future, resulting in a decrease in current marginal compliance cost and a rise in expected marginal compliance cost. An equilibrium is achieved when current marginal compliance cost is equal to the discounted expected marginal compliance cost.

If the maximum banking limit is reached, λ_t is zero, $\min(B_t + e_t - M_t, 0.2M_{t+1}) = 0.2M_{t+1}$, and (10) becomes

$$\dot{c}_t(e_t - \varepsilon_t) = -\beta \frac{\partial E_t V_{t+1}(\min(B_t + e_t - M_t, 0.2M_{t+1}), t+1)}{\partial e_t} = \beta \frac{\partial E_t V_{t+1}(0.2M_{t+1})}{\partial e_t} = 0. \quad (14)$$

Marginal cost is zero only if no extra ethanol is consumed and

$$e_t = \varepsilon_t. \quad (15)$$

In this case, the available RIN stock could be greater than the number of RINs that can be banked so that additional RINs have no value. The optimal condition for ethanol consumption requires that the marginal compliance cost of meeting the mandate is zero which implies by (15) that consumption produced is the same as if there is no mandate and no banking and borrowing of RINs.

When the borrowing constraint is binding at time t , $e_t - (M_t - B_t) = -0.2M_{t+1}$, $\lambda_t > 0$. Then we have

$$\dot{c}_t(e_t - \varepsilon_t) = \beta E_t(\dot{c}_{t+1}(e_{t+1} - \varepsilon_{t+1})) + \lambda_t. \quad (16)$$

Equation (16) says that the expected marginal compliance cost grows less than the rate of interest, the ethanol producer would have an incentive to borrow additional RINs from the future. However there is a regulatory constraint restricting maximum borrowing, resulting in a binding borrowing constraint.

From the above discussion, we know that expected marginal compliance costs increases at the rate of interest whenever the constraints on borrowing and banking are not binding. Marginal compliance costs grow by less than the interest rate when the borrowing constraint binds, and marginal compliance costs are zero when the banking constraint binds.

Expected marginal compliance costs equal the expected RIN price which is the difference between the marginal cost of producing ethanol and marginal benefit of using ethanol

(McPhail (2010)). The marginal cost of producing an extra gallon of ethanol equals feedstock cost plus a constant conversion cost. Corn is assumed to be the feedstock. Let Y_e be net corn use for producing a gallon of ethanol accounting for byproducts produced per bushel of corn processed in ethanol production⁴. Per-gallon conversion cost is assumed to be a constant c_e . Assume that the technology for producing ethanol from corn is constant for all time periods so that Y_e and c_e do not change with t . Thus $p_{ct}/Y_e + c_e$ is the marginal cost of ethanol production. With more corn devoted to produce ethanol, corn price rises and marginal production cost increases. This specification connects the ethanol market to the corn market. The marginal benefit of blending ethanol equals the ethanol price p_{et}^d along the ethanol demand curve. Thus the RIN price in any period equals $p_{ct}/Y_e + c_e - p_{et}^d$. The model does not impose any production constraint. In reality, there is an upper limit on how much ethanol the U.S. industry can produce. Imposing this upper limit on model solutions would do little to change our results because the mandates we consider are binding in almost all states of the world and below industry production capacity.

Our model treats RINs as a storable commodity. Just as storing stabilizes corn prices under yield uncertainty, RIN storage serves the same function, helping to stabilize ethanol and corn prices under an ethanol mandate in a stochastic world. Stock levels of corn are determined by the no-arbitrage profit equation that compares the value of storing one more unit with the value of consuming one more unit. Without borrowing and banking constraints, RIN storage is determined by a no-arbitrage profit condition that equates the marginal cost of meeting the mandate in this period to the discounted value of the expected cost of meeting the mandate in the next period. The difference between corn storage and RIN storage is that corn that is stored can be consumed in the next period but stored RINs cannot be consumed as ethanol in the next period. However, because stored RINs can be used for future compliance, they affect equilibrium ethanol production. If ethanol production is greater than the mandate, total ethanol production will be consumed and the surplus RINs

⁴The details of modeling the net corn production for ethanol can be found in Lapan and Moschini (2012), page 227.

will be stored for future use up to the banking constraint.

Markets are in equilibrium when corn supply equals corn demand, when ethanol production equals ethanol consumption (ethanol cannot be stored) and when there are no arbitrage profit possibilities from storing RINs or corn. The total supply of corn at time t is denoted as $TS_t = A_t y_t + x_t$, where A_t is the acreage harvested at time t which is decided by farmers in time $t - 1$: $A_t = A(E_{t-1}(p_t))$ and where y_t is the corn yield at time t . Total corn demand is the sum of non-ethanol demand $D_c(p_{ct})$, corn for ethanol $\frac{e_t}{Y_e}$, and storage x_{t+1} . Equilibrium conditions are sequences of quantities $\{e_t, D_{ct}, x_{t+1}, A_{t+1}\}_{t=0}^{\infty}$ and prices $\{p_{ct}, p_{et}\}_{t=0}^{\infty}$ such that (i) the quantities solve the arbitrage profit conditions given the sequence of prices, (ii) the corn market clearing condition is met as shown by equation (17), (iii) and the ethanol market clears through equation (18).

$$\forall t, A(E_{t-1}(p_{ct}))y_t + x_t = D_c(p_{ct}) + \frac{e_t}{Y_e} + x_{t+1} \quad (17)$$

$$e_t = D_e(p_{et}^d, p_{gt}) \quad (18)$$

3 Model Assumptions and Solution Method

3.1 Parameter Specification

The model is solved for the 2016/17 corn marketing year (which begins on September 1) through the 2021/22 marketing year. The 2015/16 marketing year data is assumed known. All parameters are calibrated to either market data or published literature.

The ethanol demand curve is taken from Pouliot and Babcock (2014) who estimate U.S. E85 demand using Brazilian data. The demand for E85 is low when the cost per mile driving on E85 is higher than E10. But their demand curve becomes quite elastic when E85 prices become competitive with E10. Eventually demand becomes inelastic due to limits on the number of stations that sell E85. The range of E85 quantities where demand is elastic

increases if additional E85 fueling stations become available because the bottleneck limiting demand for E85 is access to fueling stations not the number of flex vehicles.

The two stochastic variables in the model are corn yield and gasoline prices. Mean corn yield is increased by two bushels per acre per year to account for average observed yield increases in the last three decades. The amount of yield variability is estimated using historical deviations from trend yield. Yield is assumed to be beta-distributed with a standard deviation of yield being kept constant from 2014 through 2019. The beta distribution has been used in many studies to capture potential skewness (Babcock and Hennessy (1996), Nelson and Preckel (1989)). Corn yields are mainly impacted by weather and we assume corn yield is not affected by corn price. This is consistent with findings by Steven and Wolfram (2011) who argue that the yield-price elasticities for corn can not be larger than 0.1 and are most likely zero. Mean wholesale gasoline prices are set to the average of RBOB gasoline futures prices in each marketing year. Gasoline prices are assumed to be lognormally distributed which is consistent with the observation that percentage changes in gasoline prices across two periods are normally distributed.

Ethanol yield is fixed at 2.7 gallons per bushel of corn processed. To facilitate calculations, approximately 30 percent of each bushel processed is returned to the corn market as feed. Thus the net yield of ethanol per bushel of corn processed is about 3.86 gallons per bushel when the value of the returned feed is equal to the price of corn. The non-corn cost of producing ethanol is fixed at \$0.50 per gallon.⁵

We assume a constant elasticity demand curve. We calculate the non-ethanol demand elasticity for corn by a share-weighted average elasticity of demand for corn used as food, exports and feed. The position of the demand curve for each year of the projection period is based on USDA (2016) long term agriculture projections. The elasticity of US harvested

⁵Our assumption that non-corn production costs are constant somewhat overstates the short-run supply response of the ethanol industry. We make this assumption because estimating the short-run supply elasticity is beyond the scope of this paper and we have seen no estimates in the literature. Lags between changes in measured spot profit levels and changes in production could be caused at least in part to hedging strategies that delay the transmission of spot price changes to actual changes in profitability.

corn acreage is fixed at 0.2 (Peterson and Tomek (2005)). The physical cost of storing corn from one harvest to the next marketing year is fixed at \$0.36 per bushel. A function relating marginal convenience yield to stocks to use ratios is estimated using data from 1989 to 2012. The details of the calibration are found in the supporting material.

3.2 Solving the Model

Corn and RIN storage levels are the two state variables in our model. The model is solved by finding the expected corn price and expected ethanol price functions which depend on these two state variables. These unknown functions need to satisfy no-arbitrage profit conditions for corn and RIN storage and corn acreage must maximize farmer expected profits.

For corn, coming out of normal production years, corn price this year plus the physical cost of storage equals the expected corn price next year. If marginal convenience yield is high because of a short crop, then expected price next year equals this year's price plus storage costs minus the marginal value of the convenience of having a bushel of corn on hand because of supply shortages. Thus in corn-short years, backwardation can occur when next year's expected corn price is less than this year's corn price.

For RINs, the solution condition means that the expected price of RINs must rise at the rate of interest except when borrowing and banking limits are reached. The RIN price drops to zero when the banking constraint binds. Next year's expected RIN price may be less than this year's price plus interest costs when the borrowing constraint binds. This will occur when high RIN prices this year create an incentive to borrow RINs from the following year but statutory limits on borrowing have been reached.

The collocation method is used to solve the model. This method has been applied to solve other commodity storage models including Miranda (1997), Peterson and Tomek (2005) and Gouel (2013). In our model, we assume a stationary world after 2021/2022 in that we assume that non-ethanol demand and the distributions of the stochastic variables remain constant over time. Before 2021/22 mean yield increases by two bushels per acre per

year and non-ethanol demand changes are calibrated to USDA projections. There are three steps involved in using the collocation method. First, we provide initial guesses about the parameters of the functions that are used to approximate the unknown expected corn price and ethanol price functions. Second, we update the initial guesses using the corn storage and RIN storage no-arbitrage conditions. Third, approximated function solutions are obtained when updated functions converge. Details of the solution methods can be found in the supporting material.

4 Simulation Results

4.1 Distributions of Simulated Variables

In this section we use the solved model to simulate distributions of acreage, stock levels, production levels and the prices of corn, ethanol and RINs from 2016/17 to 2021/2022 under two scenarios regarding the level of ethanol mandates and the number of E85 stations. Initial conditions are the latest projections for the 2015/16 marketing year regarding corn yield, harvested acreage, and beginning stocks of corn and RINs. We generate 5,000 corn yields and gasoline prices for each marketing year. Each corn yield and gasoline price are drawn independently from the beta distribution and log normal distribution in the given time period. The n th state of world can be written as $((y_{16/17}, p_{g16/17}^n), \dots, (y_{21/22}, p_{g21/22}^n))$. The probability of this n th sequence occurring is $1/5000$.

If we are in the n th state of world in 2016/17, we can solve for the storage decision in 2016/17 ($x_{17/18}$), harvest decision in the following year ($A_{17/18}$), beginning RIN stocks in the next period ($B_{17/18}$), quantity of ethanol ($e_{16/17}$) and non-ethanol corn consumption ($TS_{16/17} - e_{16/17}/Y_e - x_{16/17}$) given the beginning corn stock ($x_{16/17}$), beginning RIN stock ($B_{16/17}$), and acreage harvested ($A_{16/17}$) in 2016/17. Thus all prices are obtained in 2016/17. Starting from all known values of 2016/17 and if we are in the n th state of the world in 2017/18, first we need to know the values of all state variables. The beginning corn stock in 2017/18 is $x_{17/18}$ and the beginning RIN stock is $B_{17/18}$. Then we solve for all variables

of interest in 2017/18 when the n th state happens and all prices are known for 2017/18. The same method is used for solving for prices in 2018/19. After solving for the unknown variables for each of the 5,000 sequences of states we obtain distributions of prices in each period.

Table 2 shows summary statistics of the simulations for the scenario in which EPA lets the ethanol mandate increase to 14.5 billion gallons in 2016, 14.8 billion gallons in 2017 and 15 billion gallons after that. This scenario is consistent with what EPA has proposed for 2017 and is likely to propose for 2018. Because this model is solved on a marketing year basis, the mandates that are imposed on the model solutions are 14.7 billion gallons for the 2016/17 marketing year, 14.93 billion gallons for the 2017/18 marketing year and 15 billion gallons thereafter. To allow these mandates to be met, 2,500 additional stations that sell E85 are installed in the 2016/17 marketing year and another 2,500 additional stations are built in the following marketing year.⁶ Summary statistics of output variables include the mean, median, standard deviation, maximum and minimum values.

The mean results show that the increased ethanol mandates can be met with the 2,500 additional stations in each of the first two marketing years through a combination of expanded ethanol consumption and production and a drawdown in the number of banked RINs. The first-year drawdown of banked RINs is about 0.36 billion to meet the 14.7 billion gallon mandate. Thus about 14.34 billion gallons of ethanol are actually consumed. Thereafter, ethanol production and consumption are more closely aligned, with the average size of the RIN drawdown staying around 0.15 billion to 0.2 billion in the following periods. Average corn prices rise modestly through the projection period. This modest rise hides the actual volatility in the model solutions caused by yield variability. Average harvested corn acreage stays constant at around 84.5 million acres through the projection period. Average RIN prices increase from 59 cents per gallon to 68 cents per gallon which implies

⁶This number of stations is consistent with the number that is expected to be installed in response to the U.S. Department of Agriculture's Biofuel Infrastructure Partnership, which is a subsidy program designed to increase the number of gasoline retailers who sell E85. For more information see the fact sheet at <http://www.usda.gov/wps/portal/usda/usdahome?contentid=2015/05/0157.xml>

that ethanol mandates push average ethanol consumption higher than what market demand would dictate in the absence of mandates. This level of RIN prices would likely incentivize additional investment in stations that sell E85 (or E15) which would then result in lower RIN prices. We do not, however, endogenize the installation of additional E85 pumps due to a lack of data on the response of retail installations to market incentives rather than subsidies. The standard deviation of corn price is about 31% to 35% of the mean, and that of corn storage levels is around 35%. The standard deviation of RIN price ranges from 22% to 41% of the mean, while that of ethanol production is around 6.5%.

Summary statistics of simulated values with reduced mandates and no investment in E85 stations are shown in Table 3. Average corn prices and production are modestly lower due to decreased demand for ethanol. Average RIN prices are close to 20 cents lower but even the reduced mandates push average ethanol consumption higher than market demand without mandates. With this level of RIN prices, the average RIN stock decreases each year but the levels stay higher than under increased mandate scenario. In this reduced mandate scenario, the standard deviation of corn price ranges from 29% to 34% of the mean which is a bit lower than the higher-mandate scenario, and that of corn stock is around 35%. The standard deviation of RIN price increases to 29% to 51% of the mean, while that of ethanol production is around 7%.

Table 2: Simulation Results with Higher Mandates and New E85 Stations*

	2016/17		14.7**			2017/18		14.93		
	Mean	Median	Std.Dev.	Max.	Min.	Mean	Median	Std.Dev.	Max.	Min.
Harvested Acreage	84.27	84.27	0.00	84.27	84.27	84.55	84.42	1.47	88.38	81.27
Corn Production	13.81	13.91	1.27	16.82	9.10	14.02	14.14	1.30	17.30	9.34
Corn Price	4.17	3.90	1.28	16.79	2.13	4.18	3.91	1.35	18.13	1.88
Ending Corn Stocks	1.65	1.67	0.58	3.00	0.61	1.64	1.66	0.59	3.00	0.61
Ethanol Demand Price	0.99	0.94	0.26	3.53	0.54	0.97	0.93	0.27	3.85	0.37
Ethanol Production	14.34	14.54	0.92	15.64	10.17	14.78	14.95	0.98	16.42	9.70
RIN Price	0.59	0.58	0.13	3.26	0.37	0.60	0.60	0.19	3.18	0.00
Beginning RIN Stock	1.54	1.54	0.00	1.54	1.54	1.18	1.38	0.92	2.48	-2.99
	2018/19		15			2019/20		15		
	Mean	Median	Std.Dev.	Max.	Min.	Mean	Median	Std.Dev.	Max.	Min.
Harvested Acreage	84.51	84.39	1.51	88.32	81.05	84.51	84.40	1.52	88.15	81.11
Corn Production	14.20	14.29	1.29	17.41	9.52	14.34	14.40	1.27	17.57	10.10
Corn Price	4.24	3.95	1.47	26.50	1.95	4.26	4.00	1.37	19.67	1.80
Ending Corn Stocks	1.61	1.62	0.58	3.00	0.61	1.58	1.57	0.58	3.00	0.61
Ethanol Demand Price	0.98	0.93	0.28	3.00	0.38	0.97	0.92	0.28	4.10	0.35
Ethanol Production	14.81	14.95	0.97	16.43	9.86	14.83	14.97	0.96	16.46	9.25
RIN Price	0.63	0.63	0.26	6.63	0.00	0.64	0.64	0.24	4.82	0.00
Beginning RIN Stock	1.03	1.21	1.24	3.00	-3.00	0.83	1.03	1.41	3.00	-3.00
	2020/21		15			2021/22		15		
	Mean	Median	Std.Dev.	Max.	Min.	Mean	Median	Std.Dev.	Max.	Min.
Harvested Acreage	84.50	84.41	1.48	87.95	80.91	84.37	84.26	1.46	87.69	80.93
Corn Production	14.52	14.59	1.29	18.06	10.22	14.67	14.75	1.30	17.98	10.22
Corn Price	4.24	3.95	1.42	19.09	2.16	4.21	3.93	1.43	20.69	2.03
Ending Corn Stocks	1.58	1.59	0.57	3.00	0.61	1.59	1.60	0.57	3.00	0.61
Ethanol Demand Price	0.94	0.89	0.29	3.51	0.33	0.92	0.88	0.27	2.85	0.32
Ethanol Production	14.79	14.91	0.98	16.43	9.45	14.86	14.99	0.95	16.42	9.15
RIN Price	0.66	0.66	0.24	4.59	0.00	0.68	0.67	0.27	4.92	0.00
Beginning RIN Stock	0.66	0.86	1.49	3.00	-3.00	0.44	0.62	1.53	3.00	-3.00

*We assume 2500 new E85 stations in 2016/17 and another 2500 new E85 stations in 2017/18 in this scenario. Units are billion gallons for ethanol mandate, ethanol production, and beginning RIN stock; million acres for harvested acreage \$ per bushel for corn prices, \$ per gallon for ethanol price and RIN price; and billion bushels for ending corn stocks and corn production. Ethanol demand price stands for price along the ethanol demand curve.

**Values next to the years are the ethanol mandates assumed in the scenario.

Table 3: Simulation Results with Reduced Mandates and No New E85 Stations*

	2016/17		13.87**			2017/18		13.87		
	Mean	Median	Std.Dev.	Max.	Min.	Mean	Median	Std.Dev.	Max.	Min.
Harvested Acreage	83.54	83.54	0.00	83.54	83.54	83.68	83.59	1.40	87.12	80.44
Corn Production	13.71	13.79	1.24	16.64	9.35	13.92	13.98	1.27	17.07	9.16
Corn Price	3.96	3.74	1.17	13.30	1.95	3.93	3.69	1.30	21.36	1.76
Ending Corn Stocks	1.62	1.63	0.56	3.00	0.61	1.65	1.66	0.58	3.00	0.61
Ethanol Demand Price	1.11	1.06	0.24	3.39	0.63	1.09	1.05	0.26	3.11	0.51
Ethanol Production	13.64	13.88	0.98	14.76	9.55	13.72	13.98	0.94	14.76	8.67
RIN Price	0.42	0.40	0.12	2.79	0.25	0.42	0.40	0.19	4.42	0.00
Beginning RIN Stock	1.54	1.54	0.00	1.54	1.54	1.31	1.55	0.98	2.43	-2.77
	2018/19		13.87			2019/20		13.87		
	Mean	Median	Std.Dev.	Max.	Min.	Mean	Median	Std.Dev.	Max.	Min.
Harvested Acreage	83.56	83.47	1.47	87.03	80.30	83.58	83.48	1.45	86.88	80.20
Corn Production	14.04	14.11	1.27	17.34	9.39	14.20	14.28	1.28	17.58	9.89
Corn Price	4.00	3.72	1.35	18.76	1.88	4.02	3.75	1.34	20.14	1.99
Ending Corn Stocks	1.61	1.62	0.58	3.00	0.61	1.58	1.59	0.57	3.00	0.61
Ethanol Demand Price	1.10	1.06	0.28	4.15	0.41	1.10	1.06	0.28	2.88	0.45
Ethanol Production	13.74	13.95	0.92	14.76	8.32	13.73	13.95	0.92	14.78	8.32
RIN Price	0.44	0.42	0.22	4.61	0.00	0.44	0.43	0.23	4.06	0.00
Beginning RIN Stock	1.16	1.52	1.29	2.77	-2.77	1.02	1.44	1.44	2.77	-2.77
	2020/21		13.87			2021/22		13.87		
	Mean	Median	Std.Dev.	Max.	Min.	Mean	Median	Std.Dev.	Max.	Min.
Harvested Acreage	83.54	83.45	1.42	86.70	80.19	83.36	83.26	1.38	86.46	80.08
Corn Production	14.41	14.49	1.25	17.80	10.18	14.52	14.60	1.26	17.79	9.71
Corn Price	3.94	3.68	1.27	16.17	1.90	3.94	3.69	1.32	20.72	1.86
Ending Corn Stocks	1.59	1.62	0.56	3.00	0.61	1.60	1.61	0.56	3.00	0.61
Ethanol Demand Price	1.07	1.03	0.27	2.86	0.46	1.06	1.01	0.28	3.78	0.49
Ethanol Production	13.71	13.92	0.94	14.78	8.32	13.75	13.97	0.92	14.77	8.32
RIN Price	0.45	0.44	0.23	3.51	0.00	0.47	0.46	0.24	4.84	0.00
Beginning RIN Stock	0.88	1.33	1.54	2.77	-2.77	0.71	1.14	1.60	2.77	-2.77

*We assume no new E85 stations are built in this scenario. Units are billion gallons for ethanol mandate, ethanol production, and beginning RIN stock; million acres for harvested acreage \$ per bushel for corn prices, \$ per gallon for ethanol price and RIN price; and billion bushels for ending corn stocks and corn production. Ethanol demand price stands for price along the ethanol demand curve.

**Values next to the years are the ethanol mandates assumed in the scenario.

The impact of reduced mandates can be measured by comparing the Table 3 results with the Table 2 results. A reduction in the mandate reduces corn prices about 5 to 6 percent or about 22 to 30 cents per bushel. Mean corn production drops by about 100 to 162 million bushels which is between 0.7 to 1.1 percent. Average ethanol production drops by about 5 to

7 percent from reduced mandates. Corn prices would decrease even more from this drop in demand except that the decrease in corn supply from lower planted acreage boosts average prices a bit.

Figure 1 shows the distribution of corn prices for the 2016/17 marketing year for the two scenarios considered. The distribution of corn prices is positively skewed, which reflects the negatively skewed corn yield distribution and the fact that mandates can exacerbate corn price spikes caused by short crops. The distribution with the increased mandate is shifted to the right, which represents a higher average corn price, and it is slightly flatter, which seems to indicate a bit more price variability. But the coefficient of variation of price in the two distributions are approximately equal. The increase in price variability is not greater because of the role that RIN and corn stocks play in buffering the effects of low corn yields. Corn stocks are drawn down in low yield years as are RIN buffer stocks. Due to the ability to borrow RINs from future years, the RIN stock can actually turn negative, further buffering the effects of low corn yields.

Figure 2 reports the two distributions of RIN price solutions in 2016/17. The distribution with reduced mandates is to the left of the distribution with higher mandates. The RIN price distribution under lower mandates is also more peaked than the distribution when mandates are increased and 5,000 new E85 stations are built. Comparing the figures, reduced mandates have more of an impact on the RIN price distributions than the corn price distributions.

Figure 1: Distributions of Corn Prices in 2016/17

Figure 2: Distributions of RIN Prices in 2016/17

4.2 Tail Event

The rather modest impact of a reduction in the mandate is in part due to the ability to store corn and the RIN banking and borrowing provisions of the RFS. During periods of low stocks however, even small reductions in demand can have a big impact on prices. It is useful to show the impact of a tail event with low beginning stocks of corn and banked RINs on prices and production levels.

Our tail event is defined as a yield-decreasing weather shock coupled with low beginning stocks of corn (one billion bushels) and RINs (0.5 billion RINs). Our weather shock causes corn yield to be 125 bushel per acre in 2016/17, which is consistent with the national average corn yield that occurred in the 2012 drought year.⁷ We assume that corn yield increases to the trend yields thereafter. Gasoline prices are set at the mean values for all marketing years.

Table 4 reports the results of the tail event with reduced mandates. With the reduced mandate, all banked RINs are used and 2.77 billion RINs are borrowed from the next year. Corn price soars to \$10.48 per bushel in 2016/17. Without any weather shock after 2016/17, corn prices decrease through the projection period. The RIN price goes up to \$1.50 per gallon in the short-crop year and then levels off at about 60 cents towards the last years of the projection.

The results of the tail event with a higher mandate are shown in Table 5. A comparison of prices and production levels for the tail event under the high mandate scenario and the reduced mandate scenario is reported in Table 6. An additional 0.2 billion gallons of RIN are borrowed in 2016/17 to meet the increased mandate. Corn price increases by 43 cents or 4.3 percent. The RIN price is about 10 cents higher in 2016/17 and remains around 20 cents higher in the following years. Compared to a 22 cent reduction in the corn price for the reduced mandate from the average model results, the reduced mandate in the tail

⁷In reality, good growing conditions observed in 2016 are likely to result in 2016/17 corn yields that will exceed trend line levels.

Table 4: Tail Event with Reduced Mandates

	16/17	17/18	18/19	19/20	20/21	21/22
Ethanol Mandate	13.87	13.87	13.87	13.87	13.87	13.87
New E85 Stations	0	0	0	0	0	0
Harvested Acreage	85.45	87.12	85.03	84.50	84.25	84.03
Corn Production	10.68	14.29	14.12	14.20	14.32	14.45
Corn Price	10.48	4.51	4.22	4.14	4.09	4.06
Ending Corn Stocks	0.61	1.27	1.40	1.41	1.41	1.42
Ethanol Demand Price	1.72	0.95	0.93	0.94	0.95	0.96
Ethanol Production	10.60	14.23	14.25	14.24	14.20	14.19
RIN Price	1.50	0.70	0.67	0.64	0.61	0.59
Beginning RIN Stock	0.50	-2.77	-2.42	-2.04	-1.67	-1.34

event doubled the corn price reduction. However, the percentage difference remains about the same: it is a 4.3 percent difference in the tail event and a 5 percent difference for the average model solutions. Thus the impact of a higher ethanol mandate is non-linear when we measure the impact in levels but not in percentage terms.

All our results focus solely on domestic production and consumption and we assume that both exports and imports of ethanol are zero. Thus the results for RIN prices and corn prices in a short-crop year are likely overestimated if the U.S. remains a net exporter of ethanol because decreased ethanol exports would be part of the response to a short corn crop. The impact of assuming no ethanol imports is more difficult to assess without expanding the scope of the model because imports are used to meet the advanced RFS mandates and low carbon intensity targets for fuel in California.

5 Policy Implications

A substantial part of the opposition to biofuel subsidies and mandates is the potential impact they have on the price of food. This opposition was fueled by the corn price spikes in 2008 and 2013. Corn prices reached record high levels early in 2008 and then again in 2013 due in part to strong demand for ethanol as well as the severe 2012 drought that affected

Table 5: Tail Event with Higher Mandates

	16/17	17/18	18/19	19/20	20/21	21/22
Ethanol Mandate	14.70	14.93	15.00	15.00	15.00	15.00
New E85 Stations	2500	2500	0	0	0	0
Harvested Acreage	86.18	88.38	86.13	85.54	85.24	85.00
Corn Production	10.77	14.49	14.30	14.37	14.49	14.62
Corn Price	10.92	4.78	4.48	4.37	4.32	4.28
Ending Corn Stocks	0.61	1.28	1.40	1.43	1.42	1.43
Ethanol Demand Price	1.72	0.79	0.79	0.80	0.82	0.83
Ethanol Production	11.21	15.45	15.47	15.35	15.30	15.27
RIN Price	1.61	0.93	0.88	0.84	0.80	0.78
Beginning RIN Stock	0.50	-2.99	-2.47	-2.00	-1.66	-1.35

Table 6: Impact of Reduced Ethanol Mandates for Tail Event

	16/17	17/18	18/19	19/20	20/21	21/22
Harvested Acreage	-0.728	-1.263	-1.102	-1.041	-0.989	-0.966
	-0.84%	-1.43%	-1.28%	-1.22%	-1.16%	-1.14%
Corn Production	-0.091	-0.207	-0.183	-0.175	-0.168	-0.166
	-0.84%	-1.43%	-1.28%	-1.22%	-1.16%	-1.14%
Corn Price	-0.433	-0.272	-0.260	-0.237	-0.230	-0.224
	-3.96%	-5.70%	-5.81%	-5.41%	-5.31%	-5.23%
Ending Corn Stocks	0.000	-0.014	-0.006	-0.011	-0.010	-0.012
	0.00%	-1.05%	-0.40%	-0.80%	-0.73%	-0.84%
Ethanol Demand Price	0.000	0.160	0.142	0.138	0.134	0.134
	0.00%	20.19%	18.03%	17.27%	16.35%	16.06%
Ethanol Production	-0.617	-1.224	-1.219	-1.108	-1.106	-1.087
	-5.51%	-7.92%	-7.88%	-7.22%	-7.23%	-7.11%
RIN Price	-0.112	-0.230	-0.209	-0.200	-0.194	-0.192
	-6.97%	-24.66%	-23.88%	-23.95%	-24.08%	-24.52%
Beginning RIN Stock	0.000	0.213	0.052	-0.037	-0.015	0.008
	0.00%	-7.12%	-2.12%	1.85%	0.93%	-0.61%

primary US corn growing regions. For example, the average price received by corn farmers in March of 2013 was \$7.13 per bushel. Since that peak the price of corn has dropped dramatically. In July 2014 the average price received by farmers for corn was \$3.80 per bushel (NASS (2014)). In September 2014 and again in August 2016, cash prices for corn in Central Iowa dropped below \$3.00 per bushel, a level not seen since 2006. In contrast to the large year-to-year swings we have seen in corn prices, the results presented here indicate that changes in mandate levels that have been debated in the last three years will have rather modest impacts on the price of corn. The lower mandate levels consider here would result in average corn price decreases of about 22 to 30 cents per bushel or about 5 to 6 percent. The reduction in the value of the corn crop translates into an approximate \$3 billion to \$4 billion loss of revenue to the corn industry, which explains why corn farmers want higher mandate levels. However, given the small share of retail food costs that corn represents, consumer food prices would be little affected, although farmers who feed corn to livestock would be impacted. Our results indicate that the volatility of corn prices measured by the coefficient of variation of price within a year is largely unaffected by the two mandate levels considered here. Volatility increases from the higher mandates are limited because corn and RIN stocks buffer the impact of yield shocks on corn prices.

Two stated objectives of the RFS are to reduce greenhouse gas emissions and to reduce petroleum imports. Economists are nearly unanimous that the best way to cut emissions is with a carbon tax because the cost of reducing emissions is minimized when a tax is applied equally to all major emission sources. Similarly, the most efficient way of reducing oil imports is to tax imports. But politicians rarely agree with economists' prescriptions so second-best policy instruments such as the RFS that only apply to liquid transportation fuels to meet policy objectives are utilized.

Our results show that increasing RFS mandates above levels that can be met with E10 does increase US biofuel consumption. This increase likely results in decreased petroleum imports. And unless expanded mandates result in large unintended increases in greenhouse

gas emission, substitution of gasoline with ethanol will reduce emission levels, particularly if future ethanol mandates exceed the 15 billion gallon level that can be met with corn ethanol. Thus the RFS, however inefficiently, will likely meet its stated objectives.

The question facing EPA and Congress is whether the costs of maintaining support for biofuels through the RFS are too high for the benefits that are obtained. If the costs are too great or if a more efficient policy is available, then a change in policy that prevented unneeded investment in fueling infrastructure would seem desirable. The USDA program that is currently subsidizing the installation of E85 pumps is consistent with continued EPA support for high ethanol mandates. By making E85 more available to consumers, more E85 pumps will lower RIN prices and the cost of complying with ethanol mandates that increase ethanol consumption beyond levels that would otherwise exist.

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