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Nested biofuels mandates: impacts of policy product differentiation on commodity markets

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Abstract

Biofuels policies in the US and Brazil interact in complex way and can have non-trivial implications not only for biofuels markets but also for agricultural commodity markets. These implications and potentially unintended effects can also alter the balances and targets sought for greenhouse gas emission reductions. The structure of the Renewable Fuels Standard (RFS) policy, with its nested mandates, and carved out segments, while ensuring demand for certain types of biofuels creates complexities on the functioning of markets, leading to several possible and varying configuration (captured as different corner solutions) that poses challenged to market participants and can potentially create shocks and discontinuities. We propose a stylized model of U.S. and Brazil biofuel demand, supply, and trade, embedding the structure imposed by the RFS that conceptually illustrates the possibility of this two-way trade, and establishes the pricing relationships between the different types of biofuels, that need to hold for it to occur. Renewable Identification Numbers (RIN), the instruments used to demonstrate compliance with RFS act as conduits to allow for price differentiation of homogeneous in consumption corn and sugarcane ethanol. Moreover, a stochastic quantitative version of the model is calibrated and equilibrium quantities and prices simulated, including the supply curves for RINs. Our numeric results provide evidence that RFS mandates can induce the two-way trade of ethanol across the U.S. and Brazil and the possibility of two-way trade would increase with the other advanced mandate.

Introduction

Several arguments were put forth, to justify the support for the development and deployment of biofuels as replacement for fossil fuels. Among the most widely mentioned are to develop alternatives against a growing dependency on foreign fossil fuels in a backdrop of limited supplies, obtain energy security, reduced greenhouse gases (GHGs) emissions, and promote rural development. The most widely used biofuels are ethanol and biomass-based diesel, as substitutes for gasoline and diesel, respectively. The United States and Brazil are the two largest ethanol producers, accounting for more than 85% of the world's ethanol production, with the principal feedstock being corn in the U.S. and sugarcane in Brazil (RFA 2016). While Brazil had a much longer history in producing ethanol at a large scale, and was traditionally the world's largest producer, the U.S. surpassed it in 2006, maintaining that position (and widening the gap) ever since (RFA 2016). U.S. ethanol production has increased rapidly, from 1.63 billion gallons (BG) in 2000 to 14.7BG in 2015 (RFA 2016).

Although domestic production was growing rapidly, the U.S. imported ethanol since 2004, almost all from Brazil, directly or through Caribbean Basin Initiative (CBI) countries. Despite the fact the U.S. kept importing ethanol from Brazil, it began exporting ethanol in 2010 and till the present, a large portion of it to that country. Ethanol exports exceeded ethanol imports in 2011, and every year since 2014 (Figure 1). Despite this, the U.S. exports nontrivial amounts of ethanol to Brazil. Interestingly, U.S. corn ethanol and Brazilian sugarcane ethanol, are homogeneous goods undistinguishable in consumption or by inspection, are being increasingly and simultaneously traded between the U.S. and Brazil. This exchange is defined as two-way trade of ethanol in our and other studies (Debnath, Whistance, and Thompson, 2016).

The existence of two-way trade has been previously documented and explored in the literature, mainly through the observation of differences in factor endowments, productivity, scale economics, and differentiations in quality or variety between trading countries. However, this alone cannot explain two-way trade in goods that are close or perfect substitutes for consumers, and more structure on the demand side of the markets is needed for it to emerge. For example, when sugarcane ethanol is seen as higher quality because of its environmental credentials than corn ethanol, the former can command a higher price in equilibrium. Consumer preferences result in vertical quality differentiation in this example. According to Flamm and Helpman (1987), two-way trade in vertically-differentiated goods occurs due to the difference in income distribution.

With homogeneous preferences, Sheldon and Roberts (2008) use the Heckscher-Ohlin-Ricardian approach together with the presence of external economies (Helpman and Krugman 1985) in cellulosic ethanol production to demonstrate that the U.S. exports the capital-intensive good (cellulosic ethanol), while imports the land-intensive good (sugarcane-based ethanol or corn-based ethanol). However, for the case at hand, consumers cannot differentiate the goods, and production of cellulosic biofuel occurs at low levels and not being exported. Other explanations for intra-industry trade in agricultural markets have been ruled out by Meyer et al. (2012). These include aggregation or classification issues in trade data, seasonality, and border trade.

Having excluded the previous common explanations for two-way trades to segregate markets, we turn our attention to U.S. biofuel policies. Two subsidy programs that strongly influenced the U.S. biofuel market and trade with Brazil, namely the volumetric ethanol excise tax credit¹ and ethanol tariff² expired at the end of 2011. While these policies shaped and promoted the growth of the U.S. ethanol industry, they did not provide any reason to differentiate ethanol according to the feedstock used, and cannot motivate two-way trade in corn and sugarcane ethanol. The Energy Policy Act of 2005, put forth the Renewable Fuels Standard (RFS), which mandated minimum volumes of specific renewable fuels use in the U.S. These mandates were considerably expanded with the introduction of the Renewable Fuel Standard (RFS2), which was embedded in the Energy Independence and Security Act of 2007. RFS establishes a three-level mandate hierarchy for renewable fuels based on the minimum lifecycle GHG emissions reduction of renewable fuels pathways³. The hierarchy is introduced as follows. First, there is an overall mandate at the broadest level. The advanced biofuels mandate acts as a second level, counting towards the overall mandate. The advanced and conventional biofuels mandate are introduced at a second level. The advanced biofuel mandate can be met by biomass-based diesel (biodiesel), cellulosic biofuels, and Brazilian sugarcane ethanol. Additionally, the RFS2 defined sub-mandate within the advanced biofuel mandates, carving out a specific minimum volumes for biodiesel and cellulosic biofuels. The rest of the advanced mandate is named as the other advanced mandate (Thompson et al. 2010). This structure, introduces policy induced differentiation between U.S. corn

¹ Under the volumetric ethanol excise tax credit program, gasoline suppliers who blend ethanol with gasoline are eligible for a tax credit of 45 cents per gallon of ethanol (Congressional Research Service 2012).

² All imported ethanol is subject to a 2.5% ad valorem tariff; fuel ethanol is also subject to a most-favored-nation added duty of 54 cents per gallon (Congressional Research Service 2012).

³ According to U.S. Environmental Protection Agency (EPA), the lifecycle GHG emissions reduction threshold for renewable fuel is 20%, 50% for advanced biofuels, 50% for biomass-based diesel, and 60% for cellulosic biofuel (Congressional Research Service 2013).

ethanol and Brazilian sugarcane ethanol. While sugarcane ethanol can be used to meet both the advanced and conventional mandates, corn ethanol can only be counted towards the latter (and overall mandates). With this, both commodities are differentiated by policies, and can fetch different prices in equilibrium. . Meyer et al. (2012) describe the possibility of policy induced intra-industry trade in biofuels. The differentiation, and RFS compliance is implemented through the use of Renewable Identification Numbers (RIN), which will be explained in detail below. Here we advance that the construction of supply curves for RINs as well as their pricing as ways to guide different types of ethanol to the U.S. and Brazil are a major focus of this paper.

In this study, we construct a stylized trade model between the U.S. and Brazil, paying close attention to the demand structure introduced by the RFS mandates on their biofuels markets. Additionally, we specify conditions, through which the equilibrium prices and quantities can be calculated.

Moreover, as mentioned above, a topic of interest is the determination of RIN prices of various biofuels, which are tools for the implementation of RFS mandate compliance by obligated parties. For simplicity, starting from a hypothetical case that there is no advanced mandate in place, we explore the supply of advanced RINs from sugarcane ethanol. This allows us to gain insights of the different RIN prices and trade pattern of ethanol that emerge between the U.S. and Brazil and the under conditions in which the mandates are binding or not. We then extend the model to include biodiesel as an alternative to meet the other advanced mandate, and discuss the possibility to use both biodiesel and sugarcane ethanol to meet the other advanced mandate. The intuition is that the expansion of biodiesel contributing towards the advanced biofuels mandate reduces the demand and pressure to import sugarcane ethanol, and exports of corn ethanol.

Following the conceptual analysis, we conduct a series of numerical simulations. In particular, modifying a model developed by Babcock et al. (2010), with stochastic gasoline prices and feedstock yields, we calibrate the biofuels markets to solve for market clearing prices and quantities. The average values are used to estimate the effects of RFS on U.S. biofuels market in the situation of marketing year⁴ 2013/14. We also explore the sensitivity of our results to U.S. gasoline price, Brazil ethanol production and U.S. corn yield levels.

Our results consistently show that consistent with the theoretical developments, RFS biofuels mandates, especially the other advanced mandate which differentiates U.S. corn ethanol and

⁴ Marketing year for corn and soybean starts from September 1st.

Brazilian sugarcane ethanol, induce the two-way trade between the U.S. and Brazil. U.S. biodiesel could help meet the other advanced mandate to some extent, but currently still could not eliminate U.S. dependence on imported sugarcane ethanol to meet the RFS mandates. RIN supply curves and pricing relationships between the different types of biofuels are also presented.

The Model

In this section, we establish a simple trade model to show the possibility of two-way trade in ethanol between the U.S. and Brazil. With concerns that the U.S. and Brazil accounting for over 85% of the world's ethanol production, U.S. imports of ethanol almost all from Brazil, directly or through CBI countries, and Brazil ethanol imports mostly from the U.S., we only include the U.S. and Brazil in the ethanol industry in our model. In the U.S., ethanol is mainly produced from corn, while Brazil uses sugarcane as the feedstock for ethanol. We have three commodities: a numeraire composite good, corn as food or feeds, and fuels including gasoline, U.S. produced corn ethanol and Brazil produced sugarcane ethanol. Corn ethanol and sugarcane ethanol have the same energy content. They are perfect substitutes as fuels.

Assume a representative consumer has a quasi-linear preference with utility function:

$$(1) \quad U = D_0 + f(D_c) + g(D_g + \theta D_e)$$

D_0 , D_c , D_g and D_e represent consumption of numeraire, corn, gasoline and ethanol⁵, respectively. $f(\cdot)$ and $g(\cdot)$ are increasing concave functions, while θ includes the factor that converts ethanol to gasoline energy equivalent amount⁶, also reflects the constraints on blend rate of ethanol into gasoline⁷. As consumers cannot differentiate corn ethanol and sugarcane ethanol, the less expensive ethanol would be used to blend with gasoline. Maximizing the utility function, we could get the demand function of corn, gasoline and ethanol. The demand of ethanol depends on the price ratio of ethanol to gasoline. Denote the prices facing consumers as p_c for corn, p_g for gasoline and p_e^D for ethanol.

The major elements of our model are as followings:

⁵ When ethanol is not specified as corn or sugarcane ethanol, it represents general ethanol and includes both.

⁶ The energy content of ethanol is about 2/3 of gasoline, according to National Renewable Energy Laboratory (2008).

⁷ In the U.S., conventional vehicles can only use gasoline blended with up to 10% of ethanol (E10). Small amounts of flex-fuel cars use fuels more than 10% and capped at 85% (E85). Another restriction hampering sales of E85 flex vehicles and E85 is the limited infrastructure available to sell E85 to the public. According to Renewable Fuels Association (RFA), as of mid-2012, there were only about 2904 E85 retail stations in the U.S., with a great concentration in the Corn Belt states, away from major fuels consumption states, also limited to the major Flex-fuel vehicle population (on the coasts).

1. U.S. demand for corn as food/feed, $D_c(p_c)$
2. U.S. corn supply, $S_c(p_c)$
3. U.S. demand for ethanol, $D_e(p_e^D, p_g)$
4. U.S. corn ethanol supply, $S_e(p_e)$
5. U.S. demand for gasoline, $D_g(p_e^D, p_g)$
6. Brazilian demand for ethanol, $D_e^{BR}(p_e^{BR})$
7. Brazilian sugarcane ethanol supply, $S_e^{BR}(p_e^{BR})$

p_e denotes the ethanol supply price.⁸ Corn supply equals the corn production plus the corn stocks. U.S. corn utilization includes domestic food and feed use, use for stocks, net export, and use for ethanol. In the U.S., ethanol is mainly produced from corn. We assume a constant return to scale production process following Cui et al. (2011).

$$(2) \quad x_{ce} = \min\{\alpha x_c, i_e\}$$

where x_{ce} represents corn ethanol output in gallons, x_c is corn feedstock input in bushels, i_e is the amount of other inputs or costs used in the production process, α is the number of gallons of ethanol produced from one bushel of corn.

Equilibrium

As U.S. ethanol excise tax credit and ethanol tariff expired in the end of 2011, we assume that the only policy instrument is the RFS mandates on ethanol. In order to emphasize the trade in ethanol, we set the gasoline price as exogenous, and make it stochastic in the calibration.⁹ Also, we assume that corn ethanol is only produced in the U.S., sugarcane ethanol only in Brazil, and their trade of ethanol with other countries is set to be exogenous¹⁰. We assume that the transportation cost for the trade of ethanol between the U.S. and Brazil is positive, denoted as c .

First, we specify the market equilibrium conditions with no policy instrument:

$$(3) \quad S_c(p_c) = D_c(p_c) + D_c^{other}(p_c) + \alpha \cdot S_e(p_e) \quad \text{U.S. corn market equilibrium}$$

$$(4) \quad S_e(p_e) + I_e - X_e = D_e(p_e^D, p_g) \quad \text{U.S. ethanol market equilibrium}$$

⁸ Because we need to differentiate the ethanol demand and supply price when we consider the biofuels mandates, we use different notation from the beginning. But when there are no government interventions, the demand ethanol price just equal to the ethanol supply price at equilibrium.

⁹ To make the gasoline price endogenous, we would also need to specify U.S. domestic production and imports of crude oil, and the oil refining section to make the model complete.

¹⁰ We omit the amount of their trade of ethanol with other countries in the specification of the model equilibrium. They are set to be constant and adjusted to the corresponding demand in our model calibration.

$$(5) \quad S_e^{BR}(p_e^{BR}) - I_e + X_e = D_e^{BR}(p_e^{BR})$$

Brazilian ethanol market
equilibrium

$$(6) \quad p_e = \frac{p_c}{\gamma} + c_e$$

Zero profit condition in ethanol
industry

where $D_c^{other}(p_c)$ in equation (3) denotes corn demand for stock and net exports, and c_e in equation (6) is the cost of other inputs per unit of corn ethanol produced. Considering the valuable byproducts in the ethanol production process, dried distiller grains with solubles (DDGS) which is correlated with the corn price, we adjust the parameter α and denote as γ .

The arbitrage relationships in ethanol between the U.S. and Brazil are as follows:

$$(7) \quad \begin{aligned} &|p_e - p_e^{BR}| < c && \text{No trade in ethanol between the U.S. and Brazil} \\ &p_e = p_e^{BR} + c && \text{The U.S. imports sugarcane ethanol from Brazil} \\ &p_e = p_e^{BR} - c && \text{The U.S. exports corn ethanol to Brazil} \end{aligned}$$

When no government interventions present, specifically no policies differentiating corn ethanol and sugarcane ethanol¹¹, ethanol demand price equals to ethanol supply price, and there would be no trade between the U.S. and Brazil, or only one way trade: the U.S. either importing sugarcane ethanol from Brazil or exporting corn ethanol to Brazil. Whether any trade would happen and in which direction depends on the demand and supply parameters of the U.S. and Brazil. This result is consistent with the fact that the U.S. has been an importer of sugarcane ethanol before the implementation of the RFS in 2009.

Combining equations (3) to (7), we can solve for the equilibrium prices (p_c , p_e , p_e^{BR}) and the equilibrium ethanol consumption, imports and exports.

Equilibrium with RFS Fuels Mandates

We now bring in U.S. RFS mandates into the model. First, we introduce the nested structure of these renewable fuels mandates. RFS was established in the Energy Policy Act of 2005 and expanded in the Energy Independence and Security Act of 2007. It places mandates on the consumptions of different renewable fuels based on their minimum lifecycle GHG emissions reduction level. It has an overall mandate on all renewable fuels, which include conventional fuels

¹¹ Overall renewable biofuels mandate only cannot induce two-way trade in ethanol either.

(corn ethanol) and advanced fuels. Within this overall mandate, there is a sub-mandate on the consumption of advanced fuels (cellulosic biofuels, biodiesel, and other advanced fuels). Furthermore, RFS also requires minimum quantities of cellulosic biofuels and biodiesel uses individually. Taking into account of the mandates on cellulosic biofuels and biodiesel, there is a residue of the advanced mandate (other advanced mandate), for which sugarcane ethanol, biodiesel and cellulosic biofuels can compete.

The cellulosic biofuels mandate has been set to near zero, and it cannot compete with biodiesel and sugarcane ethanol at this stage. We don't consider it in our model. In this section, we consider the equilibrium that the other advanced mandate is met by sugarcane ethanol. And we will relax this assumption to include biodiesel in the following section.

Let Q^M be the leftover overall mandate excluding the advanced mandate, and Q_{adv}^M represents the other advanced mandate. Then the overall mandate for ethanol would be $Q^M + Q_{adv}^M$. When there is policy intervention, the supply and demand prices of ethanol might differ, which depends on whether these mandates are binding or non-binding. When both mandates are non-binding, the U.S. would import more than the other advanced mandate, $I_e > Q^M$, and $p_e = p_e^{BR} + c$ at equilibrium. Conditions (3) to (6) still apply and ethanol supply price equals ethanol demand price. When both mandates are binding, U.S. ethanol demand is exogenously set to be $Q^M + Q_{adv}^M$, and $I_e = Q_{adv}^M$. Together with conditions (3) to (7), equilibrium prices and quantities can be calculated. When only the other advanced mandate is binding, only U.S. ethanol imports would be set to Q_{adv}^M , but $p_e = p_e^D$. Here the ethanol supply price is for the conventional ethanol. Next we show how these mandates are implemented and how conventional and advanced biofuels markets are separated through the compliance scheme.

RIN Prices

The mandated volumes of biofuels are enforced by the Environmental Protection Agency (EPA) through the market for biofuel Renewable Identification Numbers, which is a 38-character numeric code that is assigned to a volume of biofuel through the distribution system and ownership changes. Once the biofuel is blended, the RIN may be separated and used for compliance of the mandate. Obligated parties, including individual gasoline and diesel producers and importers, are required to meet their volume obligations set by EPA, which are based on their annual production and imports of gasoline. Obligated parties can choose to buy biofuel, blend it, and keep the RIN, or

they can enter the RIN market to buy RINs from others.¹² This compliance scheme distinguishes conventional corn ethanol and imported sugarcane ethanol, and makes it possible to price different biofuels separately.

Following Babcock (2010), the price of RIN represents the gap between the supply price and the demand price at any given amount of biofuel.

$$(8) \quad RIN_{con} = p_e - p_e^D$$

If consumption of a biofuel within a calendar year begins to lag behind the pace needed to meet the annual mandated volume, then the demand for RINs would increase, which pushes up RIN prices. The increase in RIN prices increases biofuel prices received by the producers, who will then increase biofuels production and the following blending pace.

In Figure 2, we show the equilibrium RIN prices with non-binding or binding ethanol mandates. The upward sloping curve S denotes U.S. ethanol supply, while downward sloping curve D represents U.S. ethanol demand. The market clearing price and quantity are given by P^* and Q^* . The vertical line indicates the mandated quantity. In panel (a), the mandate is not binding, with equilibrium quantity larger than the mandate, so the conventional RIN price (denoted by RIN_{con}) equals zero. In panel (b), the mandate is binding. The demand for ethanol is set exogenously to the mandate. RIN_{con} equals the gap between the supply and demand prices at the quantity of the mandate.

With the assumption that using sugarcane ethanol to meet the advanced mandate, the U.S. will always import sugarcane ethanol from Brazil, at least an amount equal to the other advanced mandate. So the supply price of the advanced biofuel and the corresponding advanced biofuel RIN price RIN_{adv} should satisfy:

$$(9) \quad p_{adv}^S = p_e^{BR} + c$$

$$(10) \quad RIN_{adv} = p_{adv}^S - p_e^D$$

Advanced RIN Supply from Sugarcane Ethanol

In the above section, we illustrate the equilibrium conditions for the conventional and advanced biofuels RIN prices, given the assumption that the other advanced biofuels mandate is met by

¹² RINs created in one year can also be carried over to the next year. But obligated parties can use only up to 20% of carry-over RINs to meet their present mandate. And RINs are only valid for two years. We don't consider carry-over RINs in our model. When the carry-over RINs are used to meet the present mandate, the demand for RINs would decrease, and the RIN price goes down. That would be one of the reasons why our RIN prices are higher than those from others study.

sugarcane ethanol imported from Brazil. Here we discuss the advanced RIN supply from the sugarcane ethanol market.

We start the discussion from a hypothetical case that there is no advanced mandate, $Q_{adv}^M = 0$. The market equilibrium is indexed by superscript 0, $(I_e^0, X_e^0, RIN_{con}^0)$. We divide our analysis into three scenarios based on U.S. ethanol trade pattern under the hypothetical case.

For scenarios that U.S. imports amount is less than that of the other advanced mandate in the hypothetical case, the comparative static analysis of the impact of adding other advanced mandate is depicted in Figure 3. U.S. demand and supply are given by D and S , D^{BR} and S^{BR} for Brazil. Corresponding market clear equilibrium prices are P and P^{BR} . To satisfy the other advanced mandate, the U.S. has to import the shortage ΔM from Brazil. Then the domestic supply in the U.S. increases from S to S_I , while Brazilian domestic supply decreases from S^{BR} to S^{BR}_I . U.S. ethanol equilibrium price drops to P_I and Brazilian ethanol price increases to P^{BR}_I . Then it is potential for the U.S. to start exporting or export more, due to the increase in U.S. excess supply and Brazilian excess demand.

Scenario 1: the U.S. Exports to Brazil when $Q_{adv}^M = 0$

If the U.S. exports corn ethanol to Brazil under the hypothetical case, $X_e^0 > I_e^0 = 0$, adding the other advanced mandate induces the U.S. to import an amount of Q_{adv}^M sugarcane ethanol. Ethanol imports enlarge the ethanol price between the U.S. and Brazil, which promotes more exports to Brazil. Therefore, the U.S. imports an amount of Q_{adv}^M sugarcane ethanol from Brazil, and at the same time exports corn ethanol to Brazil, which forms a two-way trade in ethanol between the U.S. and Brazil. At equilibrium, $I_e = Q_{adv}^M$, $X_e > 0$, and $p_e = p_e^{BR} - c$. And the advanced RIN price is always more than the conventional RIN price by an amount of two times transportation, because

$$(11) \quad RIN_{adv} = p_{adv}^S - p_e^D = p_e^{BR} + c - p_e^D = p_e - p_e^D + 2c = RIN_{con} + 2c$$

When the mandate is binding under the hypothetical case, $RIN_{con}^0 > 0$, after adding the other advanced mandate, the conventional ethanol mandate still binds. Combining U.S. and Brazilian ethanol market equilibrium conditions, $D_e(p_e^D, p_g) = Q^M + Q_{adv}^M$ and $p_e = p_e^{BR} - c$, we have

$$(12) \quad S_e(p_e) + S_e^{BR}(p_e + c) = Q^M + Q_{adv}^M + D_e^{BR}(p_e + c)$$

$$(13) \quad \frac{dp_e}{dQ_{adv}^M} = \frac{1}{\frac{dS_e}{dp_e} + \frac{dS_e^{BR}}{dp_e^{BR}} - \frac{dD_e^{BR}}{dp_e^{BR}}} > 0$$

where $dS_e/dp_e > 0$, $dS_e^{BR}/dp_e^{BR} > 0$, and $dD_e^{BR}/dp_e^{BR} < 0$. Equation (13) implies that the supply price of ethanol in the U.S. increases with Q_{adv}^M . The demand price decreases with the other advanced mandate. Then the conventional RIN price increases as the other advanced mandate increases, as depicted in panel (a) of Figure 4.

When the mandate is not binding under the hypothetical case, $RIN_{con}^0 = 0$, U.S. imports of sugarcane ethanol will squeeze out the same amount of corn ethanol from the domestic market. So when the other advanced mandate is less than U.S. excess domestic supply beyond Q^M , the conventional mandate is still non-binding. As the other advanced mandate increases, the conventional mandate will eventually bind and the relationship between the RIN prices and the other advanced mandate is identical to the binding case, as shown in panel (b) of Figure 4.

Scenario 2: No Trade between the U.S. and Brazil when $Q_{adv}^M = 0$

If there is no trade in ethanol between the U.S. and Brazil under the hypothetical case, $X_e^0 = I_e^0 = 0$, similar as scenario 1, adding the other advanced mandate induces the U.S. to import an amount of Q_{adv}^M sugarcane ethanol, which increases the likelihood of U.S. exports.

When the mandate is binding under the hypothetical case, $RIN_{con}^0 > 0$, after adding the other advanced mandate, the conventional ethanol mandate continues to be binding. U.S. imports of sugarcane ethanol increase its potential to export corn ethanol to Brazil. When the other advanced mandate is too small to incentive the U.S. to export, there would be a one-way trade from Brazil to the U.S., $I_e = Q_{adv}^M$ and $X_e = 0$. Together with $D_e(p_e^D, p_g) = Q^M + Q_{adv}^M$, we have

$$(14) \quad S_e(p_e) + Q_{adv}^M = Q^M + Q_{adv}^M = D_e(p_e^D)$$

So U.S. ethanol supply price remains the same, while U.S. ethanol demand price decreases with the other advanced mandate. For Brazil, domestic supply decrease pushes up the ethanol price. Therefore, both conventional and advanced RIN prices increases with the other advanced RIN mandate. But the gap between RIN_{con} and RIN_{adv} is less than $2c$, because

$$(15) \quad RIN_{adv} = p_e^{BR} + c - p_e^D = RIN_{con} + c + p_e^{BR} - p_e < RIN_{con} + 2c$$

where $|p_e^{BR} - p_e^S| < c$ is due to the condition that there is no trade in corn ethanol between the U.S. and Brazil. However, increases in the other advanced mandate will eventually induce the U.S. to export corn ethanol to Brazil, and the gap between the conventional and advanced RIN price will then remain at $2c$ as in Figure 5 (a).

When the mandate is not binding under the hypothetical case, $RIN_{con}^0 = 0$, if the other advanced mandate is so small that the conventional mandate continues to be non-binding, then RIN_{con} remains at 0, while RIN_{adv} would be positive but less than $2c$, and increasing with the other advanced mandate. But eventually, increases in the other advanced mandate will lower U.S. demand enough to make the conventional mandate bind (Figure 5 (a)). It is also possible that increases in the other advanced mandate induce the U.S. to export to Brazil with U.S. conventional mandate still non-binding, which instead creates the situation in Figure 4 (b).

Scenario 3: the U.S. Imports from Brazil when $Q_{adv}^M = 0$

When the U.S. imports from Brazil under the hypothetical case, $I_e^0 > X_e^0 = 0$, with the advanced mandate, imported sugarcane ethanol is used to meet the advanced mandate first.

When the mandate is binding under the hypothetical case, $RIN_{con}^0 > 0$, imports are diverted to meet the other advanced mandate, so the conventional mandate still binds. U.S. ethanol supply price would increase to encourage more production and imports to meet the conventional mandate. As long as the U.S. uses sugarcane ethanol to meet the conventional mandate, the conventional RIN price equals the advanced RIN price as the following:

$$(16) \quad RIN_{adv} = p_e^{BR} + c - p_e^D = RIN_{con}$$

Demand price decreases to reach the increased overall mandate. So both RIN prices are positive and increasing with the other advanced mandate. However, increase in the other advanced mandate will eventually result in all imported sugarcane ethanol being used to meet the other advanced mandate. Further increase will lower U.S. domestic supply price and increase Brazilian ethanol price, which makes it non-profitable for the U.S. to import more than the other advanced mandate. Then the advanced RIN price will exceed the convention RIN price, as shown in Figure 6 (a).

When the mandate is not binding under the hypothetical case, $RIN_{con}^0 = 0$, if the other advanced mandate can be met by the imported sugarcane ethanol and the conventional mandate is still non-binding, both the conventional and advanced RIN prices are zero. However, as the other advanced mandate increases, if U.S. imports more than the amount of the other advanced mandate, the conventional mandate will eventually bind. Then both RIN prices become positive and increase with the other advanced mandate, as illustrated in Figure 6 (b). It is also possible that as the other advanced mandate increases the advanced mandate binds with the conventional mandate non-

binding. Then the U.S. will not import more than the other advanced mandate, as the situation in Figure 5 (b).

In summary, both the conventional and advanced RIN prices are non-decreasing with the other advanced mandate. We also get insights of the biofuels RIN prices from the trade pattern between the U.S. and Brazil. The price gap between the conventional and advanced RIN is two times transportation cost when there is two-way trade. When the U.S. only imports from Brazil the amount of the other advanced mandate, the price gap is less than $2c$. As long as the U.S. imports more than the other advanced mandate, the conventional RIN price equals the advanced RIN price.

In the next section, we take into account of the competence from an alternative source of advanced biofuels, biodiesel. For ease of comparison, we simplify the above discussion about the advanced RIN supply from imported sugarcane ethanol. When the U.S. imports from Brazil with non-binding conventional mandate in the hypothetical case, the advanced RIN price starts from zero and becomes positive as the other advanced mandate increases (Figure 7 (a)). Otherwise, the advanced RIN price is always positive and non-decreasing with the other advanced mandate (Figure 7 (b)). In this latter case, denote RIN_{sc}^0 as the hypothetical minimum advanced RIN price.

Advanced RIN Supply from Biodiesel

In the above model, we assume that the other advanced mandate is met with imported sugarcane ethanol. Actually, multiple fuels are certified as advanced biofuels that can be used to meet the advanced mandate. The most important biofuel that qualifies is biodiesel made from soybean oil, animal fats or waste grease, which means that it is a substitute for sugarcane ethanol in meeting the other advanced mandate¹³. A complication of including biodiesel is that it also has a mandate that only it can meet before any volume is available to meet the advanced mandate. We first examine the biodiesel market with only the sub-mandate just for the biodiesel (denoted as Q_{bd}^M). Then add in the other advanced mandate and analyze the advanced RIN supply from biodiesel. With only the biodiesel sub-mandate, market clearing condition and corresponding biodiesel RIN prices are shown in

Figure 8. Biodiesel demand and supply curves are denoted as D and S , with equilibrium price and quantity (P^{**}, Q^{**}) . The vertical solid line is the amount of the biodiesel sub-mandate. If the

¹³ According to RFS, Biodiesel could also compete with corn ethanol to meet the conventional mandate. But currently the biodiesel RIN price is still much higher than conventional RIN price. Biodiesel has little advantage to compete with corn ethanol to meet the leftover overall mandate. We omit this possibility in our model.

biodiesel mandate is not binding, with $Q^{**} > Q_{bd}^M$, the biodiesel supply price P_{bd}^S equals the biodiesel demand price P_{bd}^D , and biodiesel RIN price RIN_{bd}^0 is zero. If the biodiesel mandate is binding, the demand for biodiesel is exogenously set to Q_{bd}^M . The biodiesel RIN price is positive and equals the gap between the biodiesel supply and demand prices, represented by $a - b$.

Next, we consider the case with the other advanced mandate met by biodiesel. Adding the other advanced mandate works as an increased biodiesel mandate. If the biodiesel sub-mandate is binding, $RIN_{bd}^0 > 0$, it remains binding with the other advanced mandate. The increased mandate leads to a higher supply price and a lower demand price as depicted in

Figure 8 (b). The dotted vertical line is the summed mandate. The advanced RIN price exceeds the initial biodiesel RIN price, because the price gap increases from $a - b$ to $e - f$. So when the biodiesel sub-mandate is binding, the advanced RIN price is always positive and increasing with the other advanced mandate (Figure 9(b)). If the biodiesel sub-mandate is non-binding, $RIN_{bd}^0 = 0$, when the other advanced mandate is small enough that the increased mandate is still non-binding, the advanced RIN price would be zero (

Figure 8 (a)). But as the other advanced mandate increases, it will eventually bind and the advanced RIN price will become positive and increase with the other advanced mandate (Figure 9 (a)).

Equilibrium for the Advanced RIN with Biodiesel

Considering the competition between biodiesel and imported sugarcane ethanol to meet the other advanced mandate, there are three possibilities to meet the other advanced mandate: (1) use sugarcane ethanol only; (2) use biodiesel only; (3) use both sugarcane ethanol and biodiesel. If only use one fuel to meet the other advanced mandate, the advanced RIN price must not be greater than that of using any of the other fuel. Otherwise, both fuels would be used to meet the other advanced mandate. The conditions for interior solutions are:

$$(17) \quad Q_{sc} + Q_{bd} = Q_{adv}^M$$

$$(18) \quad RIN_{adv} = RIN_{sc} = RIN_{bd}$$

where Q_{sc} and Q_{bd} are the corresponding amounts of the other advanced mandate that are met by sugarcane ethanol and biodiesel. RIN_{sc} is the advanced RIN price when hypothetically using

sugarcane ethanol to meet an amount of Q_{sc} advanced mandate. Similarly, RIN_{bd} is the advanced RIN price using biodiesel to meet an amount of Q_{bd} advanced mandate.

Here, we also show the determination of the shares of the other advanced mandate met by sugarcane ethanol and biodiesel by graphs. There are four possible configurations of the total advanced RIN supply from biodiesel and sugarcane ethanol, shown in the four panels of Figure 10. The advanced RIN supply from sugarcane ethanol and biodiesel are noted as ‘sugarcane’ and ‘biodiesel’, respectively. At each given advanced RIN price, the total supply of the advanced RIN (denoted as ‘total’), is the horizontal sum of the supply from sugarcane ethanol and biodiesel. RIN_{adv} is the advanced RIN price when the total supply equals the other advanced mandate, and Q_{sc} and Q_{bd} are determined by the intersections of the equilibrium advanced RIN price with the supplies of advanced RINs from sugarcane ethanol and biodiesel. Interior solutions are depicted in Figure 10, but it is easy to see how a decrease in the other advanced mandate would result in only one of the fuels being used to meet the advanced mandate.

To some extent, U.S. domestic produced biodiesel can decrease U.S. dependence on the imports of sugarcane ethanol to meet the other advanced mandate, and then reduce the possibility of two-way trade. If U.S. biodiesel is competitive, the U.S. might not have to induce more imports just because of the mandates. Competence from biodiesel to meet the other advanced mandate could also reduce the advanced RIN price. In Figure 10, the advanced RIN prices using only one fuel, corresponding to points s and b , are at least as much as the advanced RIN price using both fuels, RIN_{adv} .

Calibration

We simulate the model for the marketing year 2013/14 to estimate the potential impacts of RFS biofuels mandates on the ethanol trade pattern between the U.S. and Brazil, various RIN prices and related commodity prices. Our simulation method for U.S. and Brazilian ethanol market mainly follows Babcock et al. (2010). To account for the uncertainties in the feedstock yields, gasoline prices in the U.S., we take values of all these variables from our projected distributions. Given 500 randomly combination of draws of all these variables, we calculate the equilibrium prices and quantities. The averages are then used to show the impacts of RFS mandates in 2013/14.

U.S. Corn Market

Corn supply equals beginning stocks plus the product of yield and harvested acreage. We fix the amount of corn harvested area at 87.7 million acres as in November 11, 2012 World Agricultural Supply and Demand Estimates (WASDE)¹⁴ projections for the marketing year 2012/13. Corn beginning stock equals the projection for 2012/13 ending stock, 647 million bushels. We simulate corn yield distribution from U.S. historical corn yield data from 1980 to 2011, which is from the database of National Agriculture Statistics Service (NASS)¹⁵. We fit the linear detrended data to a beta distribution, with a mean of 161.6 bushels per acre (bu/ac), a standard deviation of 11.6 bu/ac, a maximum of 185 bu/ac, and a minimum of 100 bu/ac.

Food, feed and net export demand of corn are calibrated to linear functions, with elasticities - 0.096, -0.25 and -0.6, respectively (Babcock et al. (2010)). With evidence of the poor yield in 2012, these demands are calibrated to fit WASDE¹⁶ prices and quantities for the normal year 2010/11. Corn storage demand is modeled using a beta distribution based on the relationship between corn prices and ratios of corn storage demand to corn production. Resulting parameters are $p = 1.8$ and $q = 1.1$. Data we use are from 2000/01 and 2010/11, with the ratio constrained between 5% to 25% and corn price bounded by \$8/bushel.

U.S. Ethanol Market

According to the RFA, we assume that all U.S. corn ethanol plant produce 2.8 gallons of ethanol and 17.5 pounds of DDGS per bushel of corn, $\alpha = 2.8$.¹⁷ Following Babcock et al. (2010), we assume the price of DDGS is 85% of the corn price. The other operating cost is 74 cents per gallon ethanol produced, which is calculated from zero profit condition and assumed to be constant. $\gamma = 2.8 / (1 - 17.5/56 * 0.85) = 3.8$.¹⁸

The demand of ethanol is calibrated using a beta distribution based on its relationship with the relative price of ethanol to gasoline¹⁹. The relative price of ethanol to gasoline is constrained between 0.5 and 1.1, and the maximum consumption of ethanol is assumed to be 20 BG at the price ratio lower than 0.5 indicating that low enough ethanol price might induce investments and use of E85. As in

Figure 11, when the wholesale price ratio of ethanol to gasoline

¹⁴ See <http://www.usda.gov/oce/commodity/wasde>

¹⁵ See <http://www.nass.usda.gov/>

¹⁶ We assume that the substitution effect of the dried distillers grains with solubles (co-product of ethanol produced from corn) as feeds use if accounted for in the WASDE projections.

¹⁷ According to the RFA, dry mill facilities represent nearly 90% of U.S. total ethanol production and a modern dry mill ethanol refinery produce approximately 2.8 gallons of ethanol and 17.5 pounds of DDGS from a bushel of corn.

¹⁸ We assume 1 bushel corn weights 56 lbs.

¹⁹ Anderson (2011) also finds that ethanol demand as a substitute of gasoline is sensitive to the relative price of ethanol to gasoline.

is 0.9, ethanol demand is about 12.4 BG; when the price ratio decreases to 0.6, ethanol demand increases to 13.2 BG. The resulting parameters are $p = 180.39$ and $q = 322.35$.

Gasoline price is simulated as a lognormal distribution with a mean of \$2.55/gallon and a standard deviation of \$0.62/gallon. We estimate the mean as the average of the 2013/14 gasoline RBOB futures prices at NYMEX²⁰, and the standard deviation from the average implied volatility of gasoline RBOB options at NYMEX.

Brazilian Ethanol Market

Following Babcock et al. (2010), Brazilian ethanol demand is modeled from Brazilian auto fleet size. In Brazil, ethanol vehicles use hydrous ethanol with 5% water; gasoline vehicles use gasoline blended with anhydrous ethanol; flex-fuel vehicles (FFVs) can switch between two forms of fuel. The demand for fuel ethanol is:

$$(19) \quad D_e^{BR} = N_e L_e + \beta N_f L_e + \delta L_g (N_g + (1 - \beta) N_f)$$

N_e , N_f and N_g denote the ethanol, flex-fuel and gasoline vehicles fleet size, respectively. L_e and L_g are the volumes of fuel consumed by a vehicle per year. β is the average share of FFVs that using ethanol per year. δ is the mandatory blend level in Brazil, which is assumed to be 25%.²¹ The fleet size in 2013/14 is calibrated to the weighted average of the linear trend level in 2013 and 2014. The historical data is from Brazilian Sugarcane Industry Association (UNICA)²². Three motorcycles are treated as one car. The resulting values are 15.7 million for gasoline vehicles, 0.74 million for ethanol vehicles and 21.8 million for FFVs. Annual ethanol consumption per car (L_e) is modeled as a constant elasticity (-0.04) function of the ethanol to gasoline price ratio and adjusted to anhydrous in gallons. Coefficients are derived by fixing ethanol consumption per vehicle per year at 1885 liters at a price ratio of 0.7.²³ Considering that ethanol has only 2/3 energy content of gasoline, blended gasoline consumption per year satisfies $L_e = L_g * (0.25 * 1.05 + 0.75 * 1.5)$. For FFVs owners, whether to use gasoline or ethanol depends on the relative price of ethanol to gasoline. The relationship between δ and the relative price is modeled as a standard beta

²⁰ See <http://nymex.com/index.aspx>

²¹ In Brazil, the blend rate was lowered from 25% to 20% in October 2011, due to tight ethanol supplies. But it is expected to be back up to 25% on May 1st, 2013.

²² See <http://www.unicadata.com.ba/index.php?idioma=2>

²³ According to USDA, the Brazilian light vehicle fleet of 18 million units consumes 4.2 billion gallons per year of gasoline and 3.1 billion gallons per year of hydrated and anhydrous ethanol, and gasoline is blended with 23% anhydrous ethanol. We construct L_e by adding the ethanol consumption to the hydrous ethanol energy equivalent amount of the gasoline consumption.

distribution with $p = 2.6987$, and $q = 1.3579$.²⁴ And the transportation cost from U.S. plant to Brazilian plant is assumed to be \$0.38/gallon²⁵.

Brazilian ethanol supply is modeled as a constant elasticity function of ethanol to gasoline price ratio. The short-run elasticity is set to 0.04 to reflect the flexibility of Brazilian sugar mills to switch between producing sugar and ethanol based on the relative prices. The coefficient is calibrated to the point with 26 billion liters ethanol production at the ethanol to gasoline price ratio 0.7.²⁶

Soybean and Soybean Products Market

As the U.S., Brazil and Argentina account for about 80% of the production, and more than 85% of the exports of soybean, about 80% of the exports of soybean products, we only consider these three countries in the world supply. According to projections for 2012/13, November, 2012 WASDE report, we fix U.S. soybean harvested area at 75.7 million acres, 27.5 million hectares (ha) for Brazil and 19.7 million hectares in for Argentina²⁷. U.S. Soybean beginning stock is 140 million bushels, 17.17 million metric ton (mt) for Brazil, and 21.65 million metric ton for Argentina. Similar as corn yield, we simulate all soybean yields as beta distributions using NASS and USDA Foreign Agricultural Service (FAS)²⁸ historical yield data. U.S. soybean yield has a mean of 44.7 bu/ac (3.05 t/ha for Brazil, 2.77 t/ha for Argentina), a standard deviation of 2.8 bu/ac (0.18 t/ha for Brazil, 0.26 t/ha for Argentina), a maximum of 51 bu/ac (3.5 t/ha for Brazil, 3.2 t/ha for Argentina), and a minimum of 34 bu/ac (2.5 t/ha for Brazil, 2 t/ha for Argentina).

Soybean utilization includes crush, storage, net exports, and other demands. Crushing productivity parameters are derived through dividing soybean meals and oil productions by soybean crush quantities. Crush demands are modeled as linear function of the crush margin, which are calculated by subtracting cost of one bushel soybean from revenues of soybean meals and soybean oil produced. Storage and other demand are calibrated as linear functions of soybean

²⁴ In Babcock, Barr, and Carriquiry 2010, coefficients p and q are derived from two calibration points. In 2009, at the price ratio 0.56, the share of FFVs using ethanol was determined by UNICA to be 0.7. When price ratio rose to 0.73 in January and February, the share declined to about 0.44.

²⁵ Crago, Khanna, Barton, Giuliani, and Amaral (2010) estimated the average transportation cost from Brazil refinery to U.S. port to be 0.18 Reals per liter. With our assumption of exchange rate at 2.05 Reals per Dollar, it is \$0.33/gallon. We include a moderate cost from U.S. port to places for blending.

²⁶ The calibration point is according to 2013 Brazilian ethanol production projection in USDA GAIN report. See http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_8-21-2012.pdf

²⁷ We report their original units in the study, and adjust the units in our calculation.

²⁸ Brazilian and Argentine historical yields data is from USDA Foreign Agricultural Service. See <http://www.fas.usda.gov/padonline/>

price. Prices and quantities used to derive the parameters are from November, 2012 WASDE. Soybean net exports equal the beginning stock plus the production and excluding the crush, storage and other demands. U.S. crush, storage and other demands elasticities we use are 0.3, -0.65 and -0.1 (0.23, -0.65 and -0.03 for Brazil, and 0.2, -0.65 and -0.25 for Argentina), respectively.

Soybean meals and soybean oil beginning stocks are also from WASDE projections for storage demands in 2012/13. Soybean meals are utilized to domestic, storage and net export demands. Domestic and storage demands are calibrated as linear functions of the soybean meals price. Domestic and storage demands elasticities are -0.25 and -0.65 for all three countries. Soybean oil is utilized to domestic (non-biodiesel), biodiesel use, storage, and net export demands in the U.S., while in Brazil and Argentina we don't differentiate use for biodiesel. Elasticities for domestic and storage demands are -0.1 and -0.65, respectively. Data for all calibration points is from WASDE, and the share of soybean oil used for biodiesel is from U.S. Energy Information Administration (EIA).²⁹ Net exports equal supplies from soybean subtracting domestic and storage demands.

World demand and supply of soybean, soybean meals and soybean oil are calibrated as linear functions of the world prices. Elasticities are -0.1, -0.1, -1 for soybean and soybean meals and soybean oil, respectively. Quantities are the sum of the net exports of the U.S., Brazil and Argentina, and we use U.S. prices as the world prices. All data is from WASDE.

U.S. Biodiesel Market

We fix U.S. biodiesel production from sources other than soybean oil at 680 million gallons.³⁰ According to Paulson and Ginder (2007), one pound of feedstock can produce 0.982 pound of biodiesel. Given there are 7.4 pounds in a gallon, we have 7.55 pounds soybean oil to produce one gallon of biodiesel. The biodiesel margin per gallon equals the price of biodiesel minus the cost of required soybean oil and other costs (\$0.4/gallon)³¹. We derive the supply curve of biodiesel from soybean oil indirectly through the relationship between biodiesel production and the biodiesel margin. It is simply modeled as a linear function. Data for the share of soybean oil used for biodiesel from 2008/09 to 2010/11 is from EIA, and divide by 7.55 to get the biodiesel production

²⁹ The share of soybean oil for biodiesel use comes from U.S. bioenergy statistics table 6 "Soybean oil supply, disappearance and share of biodiesel use". See www.era.usda.gov

³⁰ This assumption follows EPA final rules about 2013 biomass-based diesel renewable fuel volume. And we assume this will not change in 2014. See <http://www.federalregister.gov>.

³¹ Again, using the cost estimations in Paulson and Ginder (2007), we define other costs as the sum of the costs of other inputs, operating expenses and capital costs minus the credits from co-products.

from soybean oil. Annual average biodiesel margins data is collected from Center for Agricultural and Rural Development (CARD)³².

The U.S. biodiesel net export is assumed to be zero.³³ And assume that biodiesel mandate is always binding.

RFS Mandates

In 2013 the RFS mandates total U.S. biofuel consumption of 16.55 billion gallons. Of this volume 2.75 BG is required to be met by advanced biofuels, and the rest 13.8 BG is mandated on renewable biofuels (conventional mandate in our study). The 2.75 BG advanced mandate includes 1.28 BG³⁴ mandate on biodiesel. Because biodiesel has about 50% more energy content than ethanol, each gallon of biodiesel counts as 1.5 gallons of ethanol equivalent. So multiplying 1.28 BG by 1.5, biodiesel mandate counts as 1.92 BG towards the advanced mandate, which leaves an amount of 0.83 BG advanced mandate (other advanced mandate in our study) to be met by sugarcane ethanol from Brazil or U.S. biodiesel. The cellulosic mandate has been set to near zero, so we neglect cellulosic ethanol in our analysis. In 2014, the total biofuel mandate increases to 18.15 BG, of which 14.4 BG mandates to be met by conventional biofuels, and 3.75 BG met by advanced biofuels. We assume that biodiesel mandate remains the same in 2014. It leaves an amount of 1.83 BG mandate to other advanced biofuels. The weighted averages of mandates in 2013 and 2014 are used for the marketing year 2013/14. The resulting conventional mandate is 14.2BG, 1.28 BG for biodiesel, and 1.5 BG for other advanced mandate. All mandates used in our study are illustrated in Table 1.

Simulation Results for 2013/14

Given the assumptions of the exogenous parameters and the distributions of the stochastic variables, we now consider alternative policy scenarios for the marketing year 2013/14. These scenarios are as follows:

1. Conventional mandate.

³² See <http://www.card.iastate.edu/research/bio>

³³ According to EIA, exports of biodiesel peaked in 2008 largely due to a perverse effect of a biodiesel tax credit in the European Union. Exports then dropped to near zero after the effect was eliminated.

³⁴ The biodiesel mandate for 2013 comes from EPA final rules about 2013 biomass-based diesel renewable fuel volume. See <http://www.federalregister.gov>

2. All mandates (Constrained), other advanced mandate can only be met by sugarcane ethanol.
3. All mandates, other advanced mandate can be met by both sugarcane ethanol and biodiesel.
4. No mandates.

Table 1 Assumptions of U.S. Renewable Fuels Mandates (BG)

Year	Conventional Renewable	Advanced Biofuels	Cellulosic Biofuels	Biomass-Based Diesel	Other Advanced	Total RFS
2013	13.8	2.75	0	1.28	0.83	16.55
2014	14.4	3.75	0	1.28	1.83	18.15
2013/14	14.2	3.42	0	1.28	1.5	17.62

Note: See <http://www.ethanolrfa.org> for the RFS mandates. *Other advanced biofuel mandates are ethanol energy equivalent volumes.

Table 2 represents the number of observations of no trade, one-way trade or two-way trade in ethanol out of our 500 simulations for each scenario. For all scenarios, we report in Table 3 the implied mandates and average results of key variables. In Table 4, results for interior solutions that using both sugarcane ethanol and biodiesel to meet the other advanced mandate are reported. Our results show that RFS mandates, especially the other advanced mandate that could differentiate U.S. corn ethanol and Brazilian sugarcane ethanol, help induce the two-way trade between the U.S. and Brazil. U.S. biodiesel could help meet part of the other advanced mandate, which then reduce U.S. imports of sugarcane ethanol to meet the RFS mandates. But this effect is far from eliminating U.S. dependence on imports from Brazil.

Conventional Mandate

In this scenario, there exist the 14.2 BG conventional mandate and 1.28 BG biodiesel mandate. We assume that biodiesel is not as competitive as corn ethanol to meet the conventional mandate, the ethanol and biodiesel markets are solved separately, given exogenous gasoline price.

Table 1 Assumptions of U.S. **Renewable Fuels Mandates (BG)**

Year	Conventional Renewable	Advanced Biofuels	Cellulosic Biofuels	Biomass-Based Diesel	Other Advanced	Total RFS
2013	13.8	2.75	0	1.28	0.83	16.55
2014	14.4	3.75	0	1.28	1.83	18.15
2013/14	14.2	3.42	0	1.28	1.5	17.62

Note: See <http://www.ethanolrfa.org> for the RFS mandates. *Other advanced biofuel mandates are ethanol energy equivalent volumes.

Table 2 reports the number of observations of different trade patterns of ethanol, given there is only conventional mandate in the ethanol market. Out of our 500 draws, there are 299 observations with the U.S. exporting corn ethanol to Brazil, 192 with no trade, and 9 with the U.S. importing from Brazil. Without the advanced mandate to differentiate U.S. corn ethanol and Brazilian sugarcane ethanol, only one-way trade or no trade of ethanol could happen between the U.S. and Brazil. Large domestic demand of ethanol in Brazil pushes up Brazilian ethanol price to \$2.41/gallon, which makes it profitable for the U.S. to export corn ethanol to Brazil even paying the transportation cost. Moreover, for 96% of the simulations, the conventional mandate is binding, mainly due to the inelastic ethanol demand assumption.

The second column of Table 3 represents the overall average results with the conventional and biodiesel sub-mandate. The average ethanol price in the U.S. is \$2.03/gallon, 27 cents below Brazilian ethanol Price. Average U.S. production is 14.59 BG, with 0.35 BG exporting to Brazil. The average conventional RIN price is \$0.75/gallon. The average biodiesel RIN price is \$1.77/gallon, high above the conventional RIN price. Because of U.S. increased production of soybean and large export demands from Brazil and Argentina, the soybean and soybean meals prices are very low in our study, while the demand for soybean oil for biodiesel use keeps the soybean oil price high.

All Mandate (Constrained)

In this scenario, we assume that all RFS mandates in place, but the other advanced mandate can only be met by the imported sugarcane ethanol. Reported in column three of

Table 1 Assumptions of U.S. **Renewable Fuels Mandates (BG)**

Year	Conventional Renewable	Advanced Biofuels	Cellulosic Biofuels	Biomass-Based Diesel	Other Advanced	Total RFS
2013	13.8	2.75	0	1.28	0.83	16.55
2014	14.4	3.75	0	1.28	1.83	18.15
2013/14	14.2	3.42	0	1.28	1.5	17.62

Note: See <http://www.ethanolrfa.org> for the RFS mandates. *Other advanced biofuel mandates are ethanol energy equivalent volumes.

Table 2, there are 43 observations with the U.S. importing more than the other advanced mandate, with low corn yield (122.4 bu/ac) and high gasoline price (\$3.53/gallon). Comparatively higher demand of ethanol together with shortage of supply induces the U.S. to import more than the other advanced mandate to meet the conventional mandate. The rest 457 observations present

two-way trade in ethanol between the U.S. and Brazil. The U.S. has to import sugarcane ethanol to meet the other advanced mandate, and at the same time, the U.S. exports the corn ethanol to Brazil due to the excess supply of corn ethanol in the U.S. together with increasing domestic demand of ethanol in Brazil. Almost all of the mandates become binding, with an amount of 15.7 BG ethanol demand in the U.S.

The overall average results are shown in the third column of Table 3. With the other advanced mandate constrained to be met by the sugarcane ethanol, U.S. imports of sugarcane ethanol increase to 1.5 BG, which induces the U.S. to export more corn ethanol. U.S. ethanol exports increase by 0.87 BG. Increased export demand causes U.S. ethanol price to increase by 11 cents/gallon. U.S. production increased from 14.59 BG to 15.44 BG. In Brazil, ethanol price increases 21 cents/gallon because of the positive net export demand. The average conventional RIN price increases by 11 cents/gallon, which implies that the conventional mandate becomes more binding, and the advanced RIN price is 75 cents, almost equal to two times transportation cost, more than the conventional RIN. All results for the soybean, soybean products, and biodiesel markets remain the same. As an average, the advanced RIN price is still lower than the biodiesel RIN price.

All Mandates

This scenario illustrates the impacts of RFS mandates on the U.S. and Brazil biofuels market. Sugarcane ethanol and biodiesel can compete as the other advanced biofuels. There are 60 observations with the U.S. importing from Brazil and 440 with two-way trade. Biodiesel can help meet 0.09 BG of the other advanced mandate, which reduces U.S. dependence on imported sugarcane ethanol to meet the other advanced mandate, and then decreases the possibility of two-way trade. But this effect is somehow very small. The U.S. still depends on imports to meet the RFS other advanced mandate.

Table 4 reports the percentage of corner and interior solutions and corresponding average RINs prices. There are 75% of our observations only using sugarcane ethanol to meet the other advanced mandate. Across these observations, the average conventional RIN price is \$0.83/gallon, and the average advanced RIN price is \$1.58/gallon, lower than the biodiesel RIN price. This implies that sugarcane ethanol has an absolute advantage as the other advanced biofuels. The rest 25% observations use both sugarcane ethanol and biodiesel to meet the other advanced mandate, such that the advanced RIN price equal to the biodiesel RIN price. And no observation uses only

biodiesel. The overall average advanced RIN price is \$1.59/gallon. Comparing with the case with constrained all mandates, alternative source of other advanced biofuels leads to a small decrease in the average corn price, ethanol production, ethanol exports and soybean meal price, while increases in average soybean, soybean oil prices.

No Mandates

To be complete, this scenario assumes a waiver of all biofuels mandates. There are 402 out of 500 observations with the U.S. exporting to Brazil, and 97 with no trade between the U.S. and Brazil. The conventional mandate reduces the probability for the U.S. to export to Brazil by 20%. However, RFS mandates induce two-way trade between the U.S. and Brazil, and increase the exports of the U.S.

If RFS mandates are waived, U.S. average ethanol demand drops from 15.63 BG to 12.8 BG, and U.S. ethanol production declines by 1.98 BG. The decrease in export demand leads to a drop of 12.1% in the U.S. ethanol price, and a drop of 10.8% in Brazilian ethanol price. The corn price decreases by 18.6% (or 99 cents/bushel). The average soybean and soybean oil prices decline by 5% and 17.5%, respectively. Soybean meals price increases by 10%. The large impacts of removing all mandates rely on the assumption that no carry-over RINs are used to meet the obligations.

Sensitivity Analysis

In this section, we investigate the robustness of our results to U.S. gasoline price and Brazil ethanol production. We vary the two variables one at a time and re-run the model for the marketing year 2013/14. And then compare the results for the scenario with all RFS mandates. Moreover, we also consider the sensitivity of our results to U.S. corn yield, which could imply the effects of shocks in U.S. ethanol supply.

U.S. Gasoline Price

We calculate the equilibriums for three fixed gasoline prices: a low gasoline price of \$1.5/gallon, the average price of \$2.55/gallon, and a high price of \$3.5/gallon.³⁵ The results for the scenario with all RFS mandates are shown in Table 5.

U.S. gasoline price has a small effect with all RFS mandates in place, which is away from the results in Thompson, Meyer and Westhoff (2008) due to the assumption of the inelastic demand of ethanol in the U.S. Because of the difficulty of the U.S. to blend more than 10% ethanol into its auto fleets, and the limitations in the investments in E85 and sales of flex-fuels vehicles, even with a high gasoline price to promote consumers' willingness to consume ethanol, the RFS mandates are still almost binding. But RFS mandates still help induce two-way trade between the U.S. and Brazil.

With U.S. biodiesel as an alternative source of the other advanced biofuels, when the gasoline price increases, biodiesel becomes comparatively more competitive. At the gasoline price of \$3.5/gallon, the percentage using both fuels to meet the other advanced mandate increases by 18%. But in general, biodiesel is still more expensive. There is only an amount of 0.08 BG decrease in the U.S. imports. But the increase in the gasoline price leads to significant drops in the RINs prices through increasing the demand prices, 55.8% in the conventional RIN price, 31.3% in the biodiesel RIN price, and 30.6% in the advanced RIN price. When the gasoline price decreases, the effects are inversed as shown in Table 5.

Brazilian Ethanol Production

With concerns about the sensitivity of our results to Brazilian ethanol production, we vary the calibration point of Brazil ethanol supply curve in our model. Shocks of Brazilian ethanol supply could also come from variations in the sugarcane yield in Brazil and changes in world sugar price. But these effects on the average results are similar as our analysis in this section. When the price ratio of ethanol to gasoline is 0.7 in Brazil, Brazilian ethanol production is recalibrated from the average 26 billion liters to a low production level of 22 billion liters and a high production level of 30 billion liters. The average results are illustrated in Table 6.

When ethanol production is low, 97% of our observations have two-way trade happening between the U.S. and Brazil, 9% more than the case with ethanol production about 26 billion liters. Facing high domestic demand, Brazilian ethanol price increases by 10 cents and imports demand

³⁵ These gasoline prices used are just to show the effects of gasoline prices on our average results. They do not provide any information of the distribution of the gasoline price.

of corn ethanol from the U.S. increase by nearly 50% (0.63 BG). U.S. ethanol price also increases by 9 cents to entice enough production to meet the increased demand from Brazil. U.S. ethanol production increases by 0.63 BG and the corn price rises by 5.8%.

The percentage using both sugarcane ethanol and biodiesel to meet the other advanced mandate increases by 13%, and U.S. ethanol imports drop by 0.07BG, which implies the shortage of sugarcane ethanol from Brazil makes U.S. biodiesel more competitive as the other advanced biofuels. This also confirms that U.S. biodiesel could reduce U.S. dependence on imports to meet RFS mandates in some extent. Soybean and soybean oil prices increase, while soybean meals price drops. The average conventional RIN price increases by 8 cents, with the average advanced RIN price two times of the transportation cost more than the conventional RIN price. The effects are inversed for a high level of ethanol production in Brazil, shown in Table 6.

U.S. Corn Yield

Low corn yield due to bad weather conditions is one of the most important shifter of U.S. ethanol supply. We compare the average market results from low, moderate and high corn yields³⁶, with results reported in Table 7.

When U.S. corn yield is as low as 143.8 bu/ac, only 40% of 100 observations have two-way trade between the U.S. and Brazil, with the U.S. exports 0.12 BG corn ethanol to Brazil, while imports 1.26 BG sugarcane ethanol from Brazil. The exports decrease by 1.53 BG from those with the moderate corn yield (162.9 bu/ac). A shortage in corn supply leads to a high corn price at \$6.83/bushel, and it could go higher if the corn yield further decreases as in 2012 that U.S. corn prices goes above \$8/bushel with the extreme low corn yield at 122.8 bu/ac. Comparing with the case with the moderate corn yield, U.S. ethanol production from corn decreases by 1.37 BG and U.S. ethanol price drops by 27.8% (\$0.55/gallon). Brazilian ethanol price also goes up by \$0.43/gallon due to the decreased exports of corn ethanol to Brazil.

Poor corn yield also increases the competitiveness of biodiesel as the other advanced mandate, 67% of 100 observations use both fuels to meet the other advanced mandate. Biodiesel helps meet 0.24 BG of the other advanced mandate, increased from 0.01 BG in the moderate corn yield case. Soybean, soybean meals and soybean oil prices all rises due to the demand for biodiesel, and also

³⁶ We sort our draws by corn yield, then compare the first, middle and last quintiles and report the average results.

due to the comparatively low soybean yield³⁷. All RINs prices increase because of the increased supply prices.

Conclusion

In this paper, we construct a stylized trade model between the U.S. and Brazil, and illustrate the equilibrium conditions. We apply the RFS biofuels mandates to the U.S. ethanol market in our model, and use this policy to explain the evidenced two-way trade between the U.S. and Brazil. This model can also be applied to explain the two-way trade of homogeneous products in other industries with similar mandates policies.

We then explore the determinations of various RINs prices and the relationship between these RIN prices. Starting from a hypothetical case that there is no advanced mandate in place, we derive the supply of advanced RINs from sugarcane ethanol. We also get insights of the RINs prices from the ethanol trade pattern between the U.S. and Brazil. Both the conventional and advanced RIN prices are non-decreasing with the other advanced mandate. With two-way trade between the U.S. and Brazil, the advanced RIN price is two times transportation cost more than the conventional RIN price. When the U.S. imports an amount of the other advanced mandate, the conventional and advanced RIN price gap is less than two times transportation cost. When the U.S. imports more than the other advanced mandate, the conventional RIN price equals the advanced RIN price. The model is then extended to take into account of U.S. biodiesel as an alternative to meet the other advanced mandate, and discuss the possibility to use both biodiesel and sugarcane ethanol to meet the other advanced mandate.

Specifically, with stochastic gasoline prices and feedstock yields from our projected distribution, we calibrate the demands and supplies of all related products to solve for market clearing prices and quantities for the marketing year 2013/14. The average values are used to estimate the effects of RFS on U.S. biofuels market. Our results consistently show that RFS biofuels mandates, especially the other advanced mandate which differentiates U.S. corn ethanol and Brazilian sugarcane ethanol, induce the two-way trade between the U.S. and Brazil. U.S. biodiesel could help meet the other advanced mandate to some extent, but currently still could not eliminate U.S. dependence on imported sugarcane ethanol to meet the RFS mandates. Variation in

³⁷ As corn and soybean in the U.S. are usually grown in the same area, and then experience the same weather conditions. Corn yield and Soybean yield has a positive correlation. We impose the correlation on the draws of these two yields. The correlation is derived from the historical data.

U.S. gasoline price, Brazil ethanol production and U.S. corn yield levels would change the magnitude of U.S. exports to the Brazil, and also impact the comparative competitiveness of U.S. biodiesel as the source of the other advanced biofuels. With the difficulty to blend more than 10% ethanol into gasoline, the U.S. ethanol demand is very inelastic and constrains the impacts of high gasoline price and high corn yield on commodities prices. And the RFS mandates also constrain the impacts of downside gasoline price change. With a poor corn yield as in 2012, RFS mandates could help explain the increase in all commodities prices and all RIN prices, and the decrease in the U.S. exports of corn ethanol.

In our model, we don't consider the flexibility of the RFS mandates that obligated parties can use carry-over RINs from last year to meet their current mandates. So the RINs prices in our study might be overestimated. Considering the carry-over RINs, the mandates can be taken as a flexible interval. And from our model, we can also derive the range of the RINs prices. Moreover, our model can also be applied to examine the effects of RFS mandates considering the dynamics of RINs supplies with the carry-over RINs.

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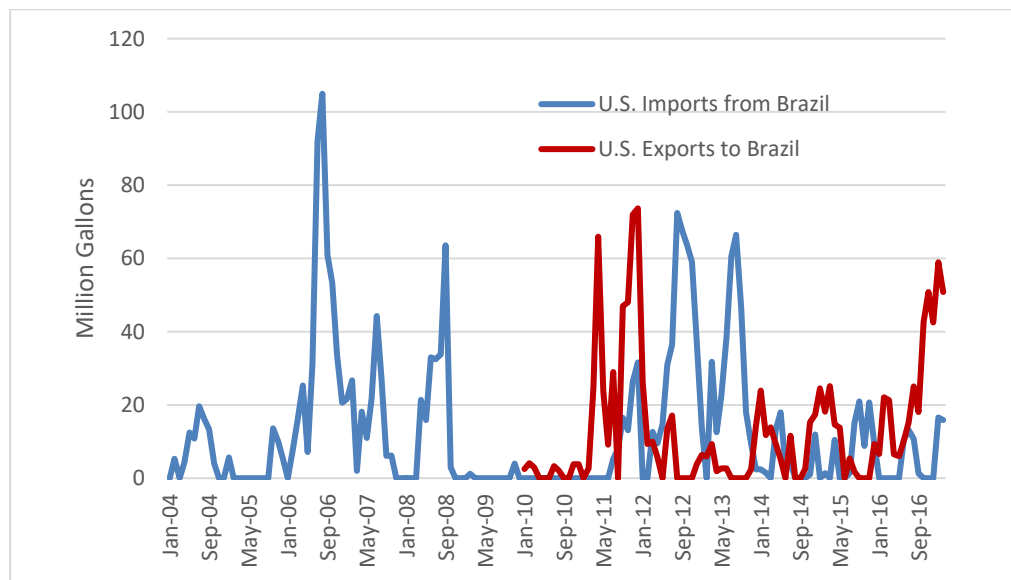


Figure 1 Trade of ethanol between the U.S. and Brazil

Data Sources: U.S. Energy Information Administration (EIA).

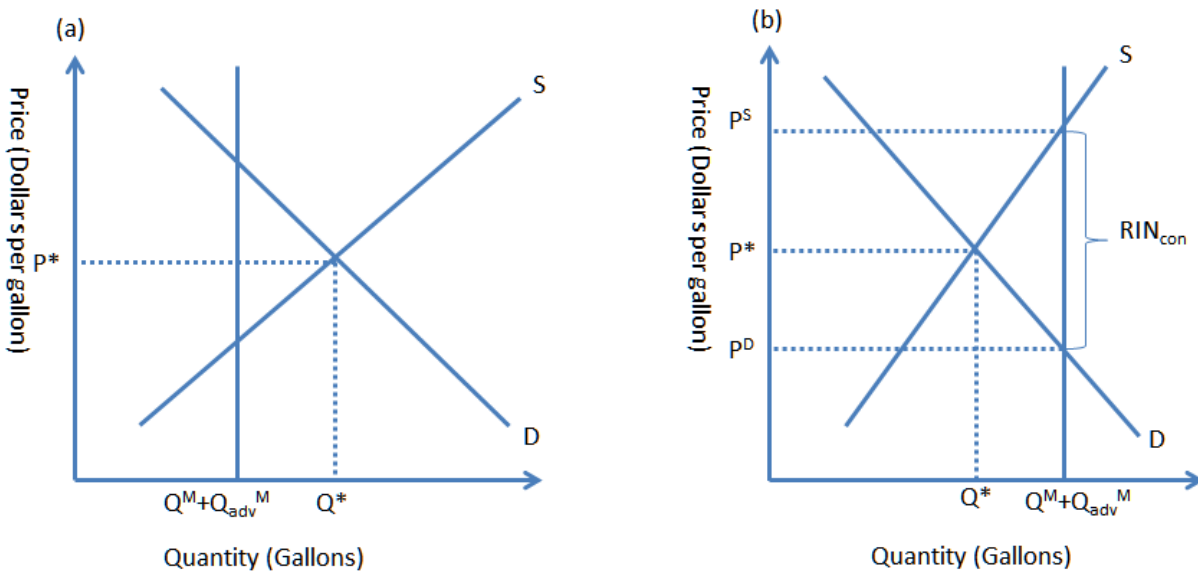


Figure 2 The determinations of RIN price when the mandate is (a) non-binding and (b) binding.

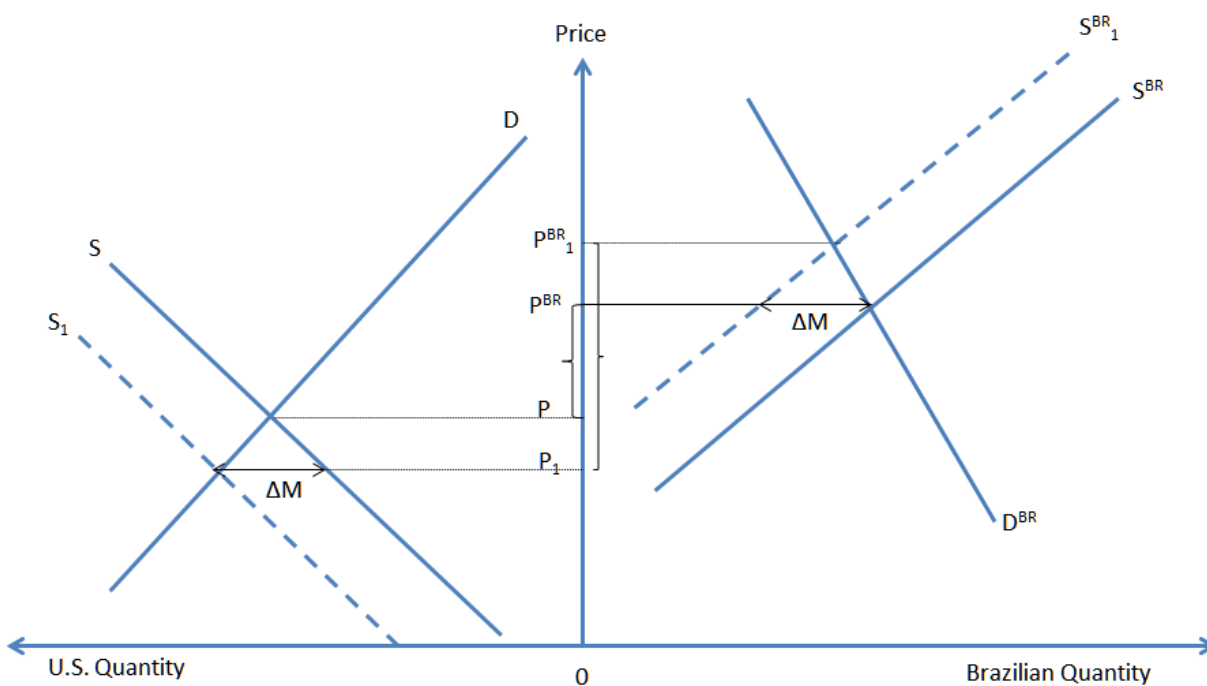


Figure 3 Comparative static analyses of the impacts of the other advanced mandate on U.S. and Brazilian markets when the U.S. has to import sugarcane ethanol to meet the other advanced mandate

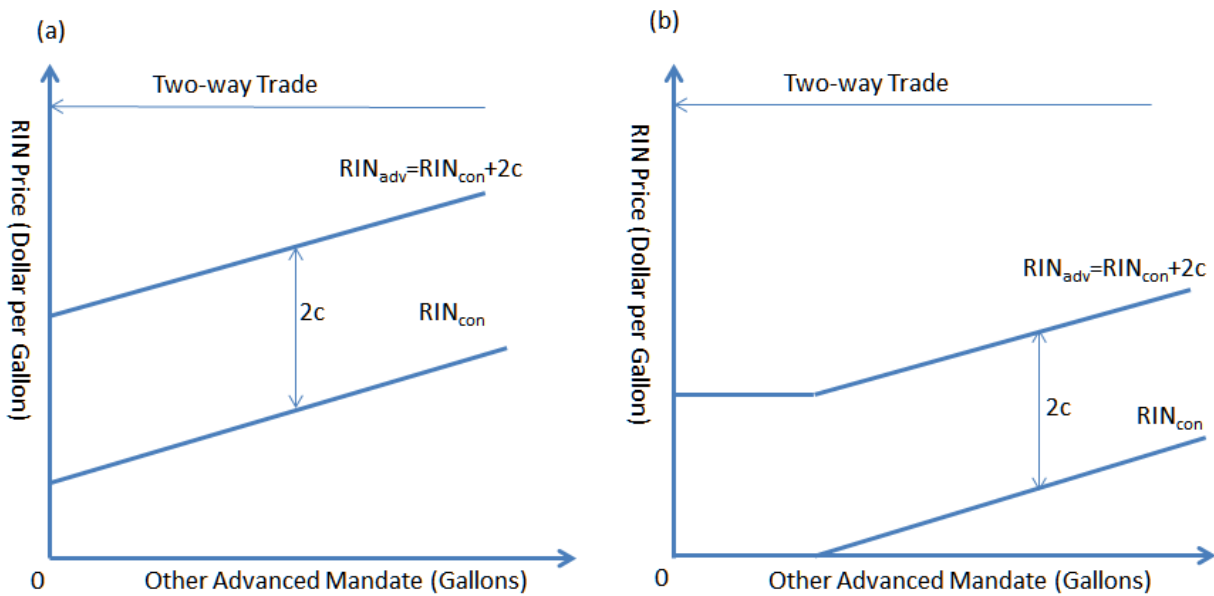


Figure 4 The relationship between RINs prices and the other advanced mandate when the U.S. exports to Brazil with (a) binding conventional mandate and (b) non-binding conventional mandate under the hypothetical case that no advanced mandate exists.

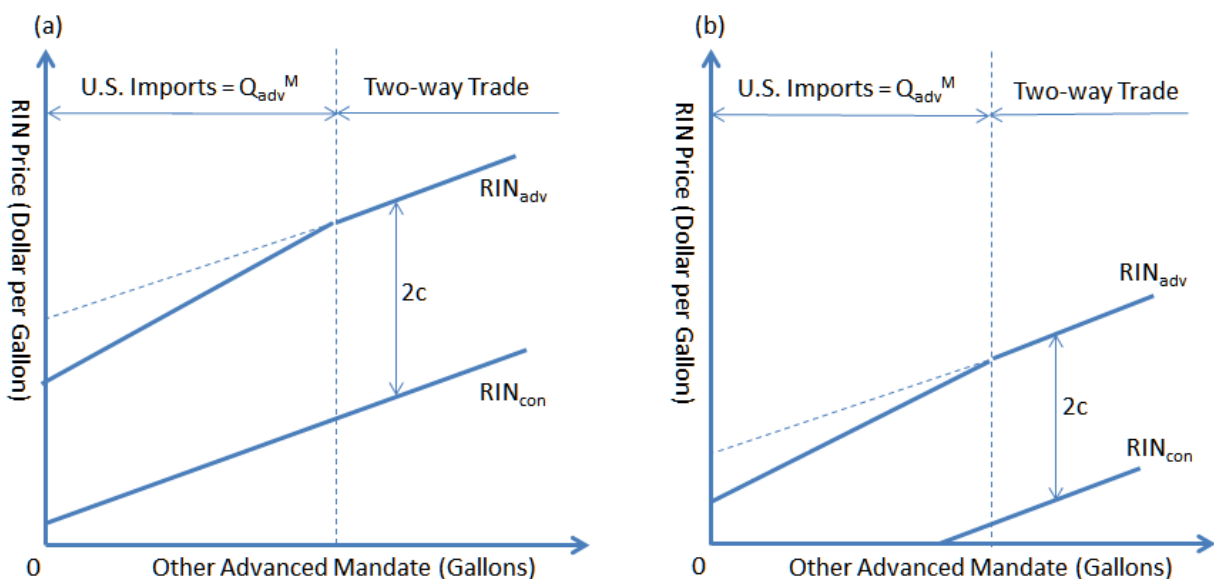


Figure 5 The relationship between RINs prices and the other advanced mandate when there is no trade between U.S. and Brazil with (a) binding conventional mandate and (b) non-binding conventional mandate under the hypothetical case that no advanced mandate exists.

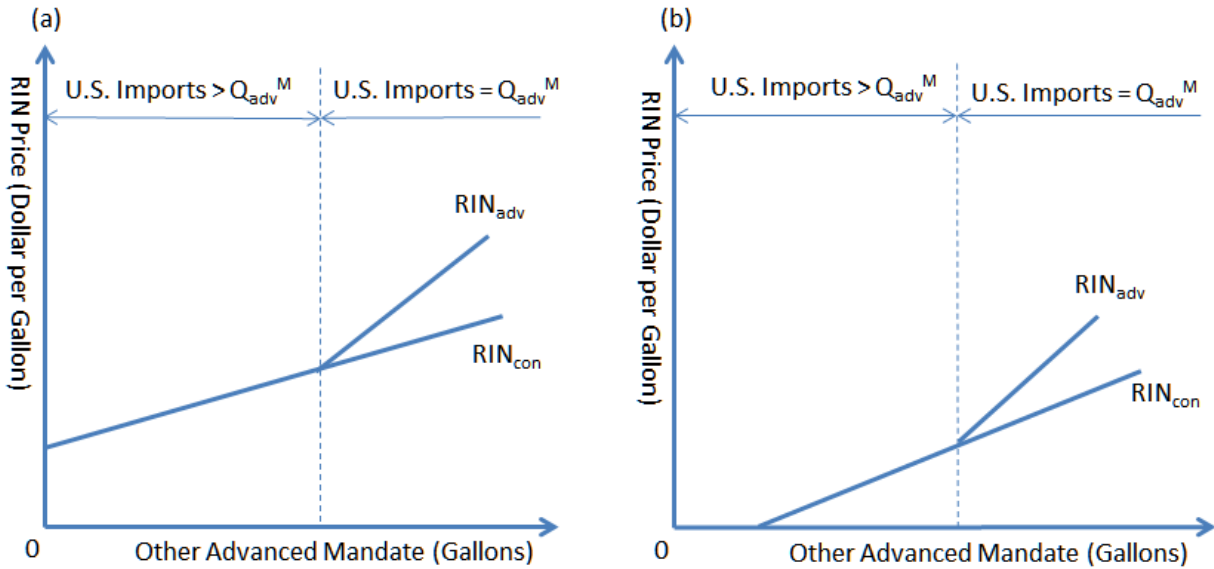


Figure 6 The relationship between RINs prices and the other advanced mandate when the U.S. imports from Brazil with (a) binding conventional mandate and (b) non-binding conventional mandate under the hypothetical case that no advanced mandate exists.

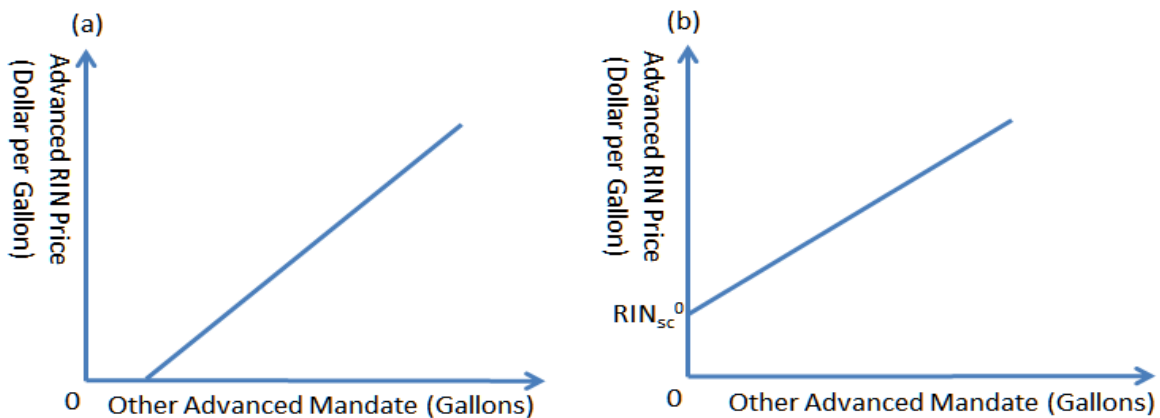


Figure 7 Advanced RIN supply from sugarcane ethanol when under the hypothetical case that no advanced mandate exists (a) the U.S. imports from Brazil with a non-binding

mandate and (b) other situations.

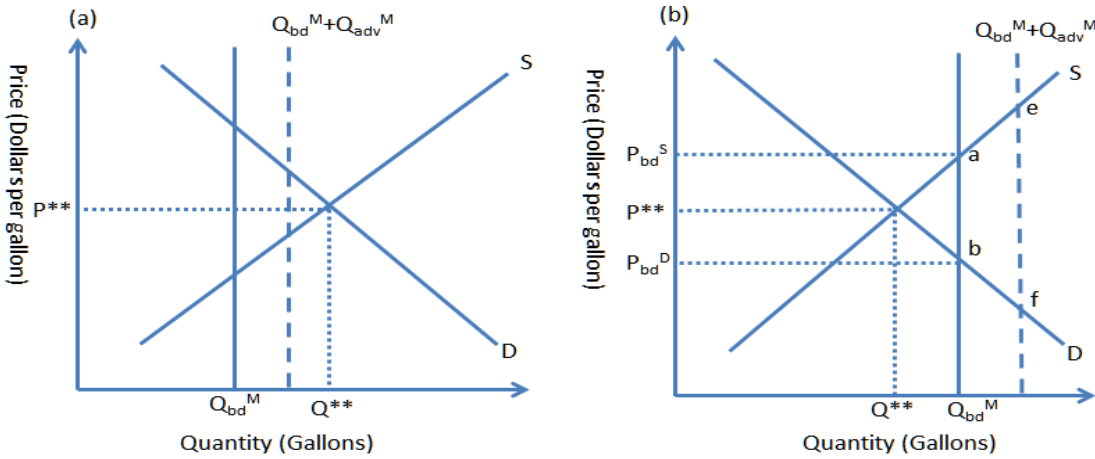


Figure 8 The determinations of biodiesel RIN price when the biodiesel sub-mandate is (a) non-binding and (b) binding.

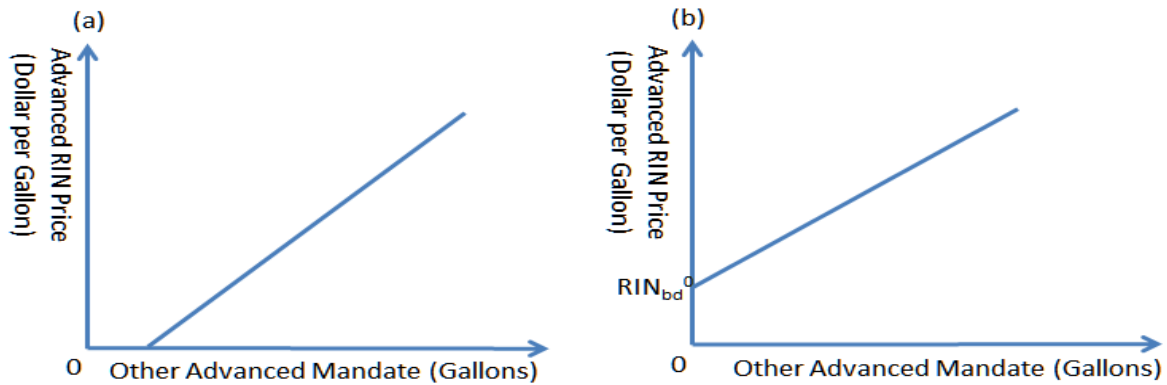


Figure 9 Advanced RIN supply from biodiesel when (a) biodiesel sub-mandate is non-binding and (b) biodiesel sub-mandate is binding.

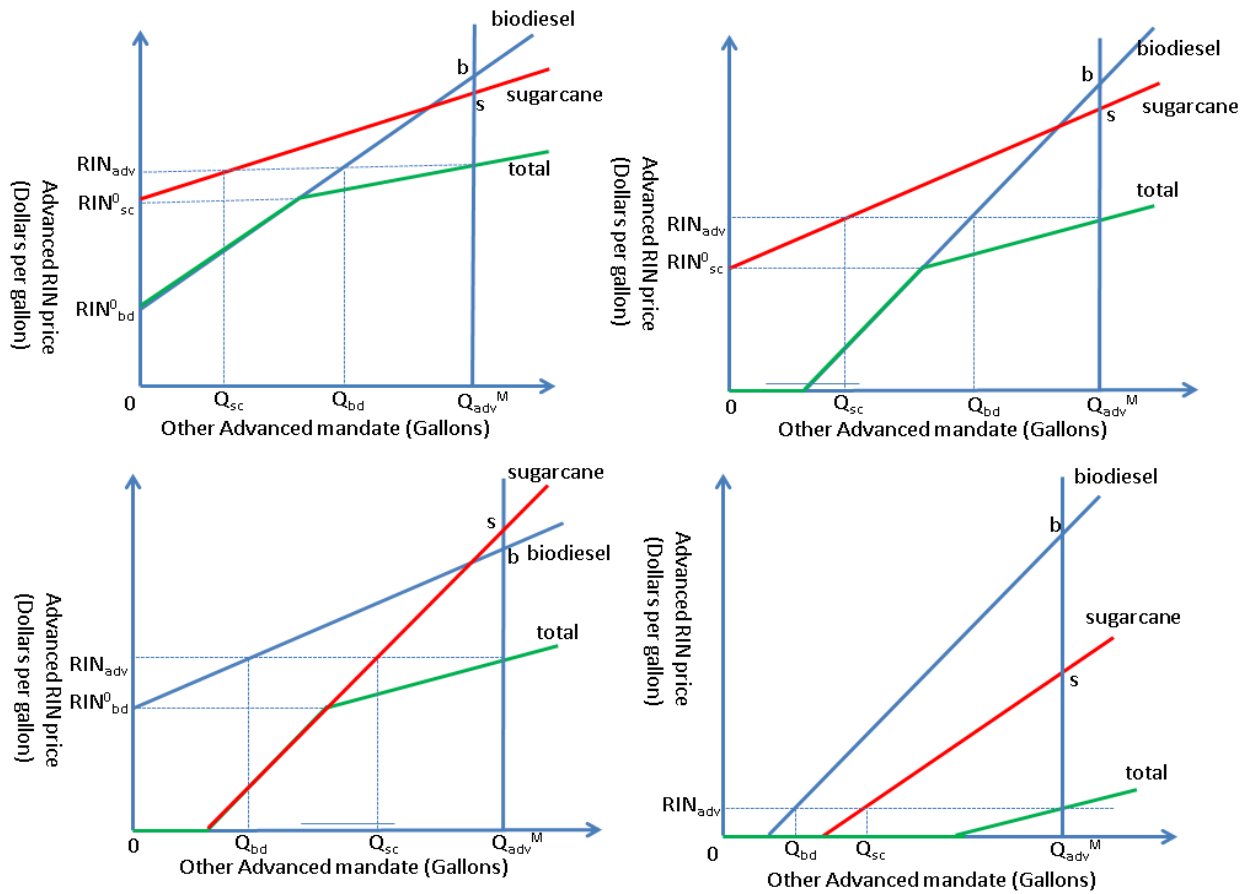


Figure 10 Advanced RIN supply when both sugarcane ethanol and biodiesel are qualified as advanced biofuels.

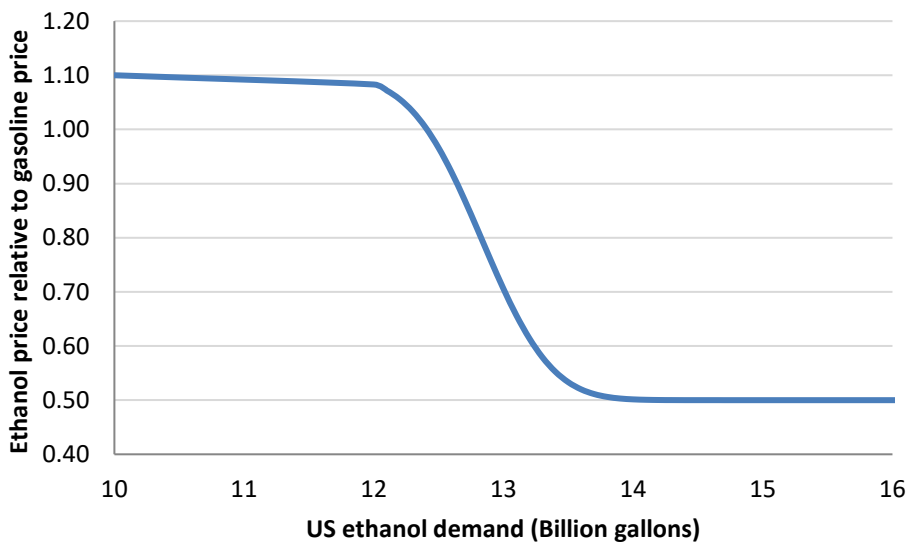


Figure 11 U.S. Ethanol Demand

Table 1 Assumptions of U.S. Renewable Fuels Mandates (BG)

Year	Conventional Renewable	Advanced Biofuels	Cellulosic Biofuels	Biomass-Based Diesel	Other Advanced	Total RFS
2013	13.8	2.75	0	1.28	0.83	16.55
2014	14.4	3.75	0	1.28	1.83	18.15
2013/14	14.2	3.42	0	1.28	1.5	17.62

Note: See <http://www.ethanolrfa.org> for the RFS mandates. *Other advanced biofuel mandates are ethanol energy equivalent volumes.

Table 2 Effects of RFS mandates on the trade of ethanol between the U.S. and Brazil

	Conventional Mandate	All Mandates (Constrained)	All Mandates	No Mandates
No Trade	192	0	0	97
U.S. Imports from Brazil	9	43	60	1
U.S. Exports to Brazil	299	0	0	402
Two-way Trade	0	457	440	0

Note: All results are expressed in number of observations out of our 500 simulations.

Table 3 Average Results for Alternative Biofuels Mandate Scenarios in 2013/14

	Conventional Mandate	All Mandates (Constrained)	All Mandates	No Mandates
Conventional Mandate (BG)	14.2	14.2	14.2	0
Biodiesel Sub-Mandate (BG)	1.28	1.28	1.28	0
Other Advanced Mandate Met by Sugarcane Ethanol (BG)	0	1.5	1.41	0
Other Advanced Mandate Met by Biodiesel (BG)	0	0	0.09	0
Corn Price (\$/bushel)	4.93	5.35	5.33	4.34
U.S. Ethanol Plant Price (\$/gallon)	2.03	2.14	2.14	1.88
Brazilian Ethanol Price (\$/gallon)	2.3	2.51	2.49	2.22
Soybean Price (\$/bushel)	8.63	8.63	8.67	8.23
Soybean Oil Price (cents/lb)	56.55	56.55	57.43	47.36
Soybean Meals Price (\$/short ton)	237.65	237.65	235.63	258.91
U.S. Ethanol Production (BG)	14.59	15.44	15.4	13.42
U.S. Ethanol Exports (BG)	0.35	1.22	1.18	0.61
U.S. Ethanol Imports (BG)	0	1.5	1.41	0
Conventional RIN price (\$/gallon)	0.75	0.86	0.86	0
Biodiesel RIN price (\$/gallon)	1.77	1.77	1.79	0
Advanced RIN price (\$/gallon)	0	1.61	1.59	0

Table 4 RIN Prices for Scenarios with All Mandates

	Percentage*	Conventional RIN Price	Advanced RIN Price	Biodiesel RIN Price
Other Advanced Mandate Met by SC	0.75	0.83	1.58	1.85
Other Advanced Mandate Met by SC and BD	0.25	0.94	1.63	1.63

Note: *Percentage of observations out of our 500 simulations. All RIN prices are in ethanol equivalent unit. SC = Sugarcane Ethanol, BD = Biodiesel.

Table 5 Market Effects of U.S. Gasoline Price

Gasoline Price	1.5\$/gallon	2.55\$/gallon	3.5\$/gallon
Percentage with Two-way Trade ¹	0.9	0.88	0.87
Percentage using both fuels ²	0.1	0.22	0.4
Corn Price (\$/bushel)	5.33	5.32	5.3
U.S. Ethanol Plant Price (\$/gallon)	2.14	2.14	2.13
Brazil Ethanol Price ³ (\$/gallon)	2.5	2.49	2.48
Soybean Price (\$/bushel)	8.65	8.67	8.7
Soybean Oil Price (cents/pound)	56.85	57.3	58.06
Soybean Meals Price (\$/short ton)	236.96	235.39	234.18
U.S. Ethanol Production (BG)	15.41	15.39	15.35
U.S. Ethanol Exports (BG)	1.21	1.19	1.14
U.S. Ethanol Imports (BG)	1.47	1.43	1.35
Conventional RIN Price (\$/gallon)	1.39	0.86	0.38
Biodiesel RIN Price (\$/gallon)	2.43	1.79	1.23
Advanced RIN Price (\$/gallon)	2.13	1.6	1.11

Note: All results are reported in the regular units in the market. All RIN prices are in ethanol equivalent unit. ¹Percentage of observations with the U.S. exporting corn ethanol to Brazil, and importing sugarcane ethanol from Brazil simultaneously.

²Percentage of observations using both sugarcane ethanol and biodiesel to meet the other advanced mandate. ³Brazilian domestic wholesale anhydrous ethanol price, with exchange rate at 2.05 reals per dollar.

Table 6 Market Effects of Brazilian Ethanol Production

	22 billion liters	26 billion liters	30 billion liters
Percentage with Two-way Trade ¹	0.97	0.88	0.75
Percentage using both fuels ²	0.38	0.25	0.05
Corn Price (\$/bushel)	5.64	5.33	5.04
U.S. Ethanol Plant Price (\$/gallon)	2.22	2.14	2.06
Brazil Ethanol Price ³ (\$/gallon)	2.59	2.49	2.38
Soybean Price (\$/bushel)	8.71	8.67	8.64
Soybean Oil Price (cents/pound)	58.2	57.43	56.7
Soybean Meals Price (\$/short ton)	233.84	235.63	237.3
U.S. Ethanol Production (BG)	16.03	15.4	14.82
U.S. Ethanol Exports (BG)	1.81	1.18	0.6
U.S. Ethanol Imports (BG)	1.34	1.41	1.49
Conventional RIN Price (\$/gallon)	0.94	0.86	0.78
Biodiesel RIN Price (\$/gallon)	1.83	1.79	1.77
Advanced RIN Price (\$/gallon)	1.7	1.59	1.48

Note: All results are reported in the regular units in the market. All RIN prices are in ethanol equivalent unit. ¹Percentage of observations with the U.S. exporting corn ethanol to Brazil, and importing sugarcane ethanol from Brazil simultaneously.

²Percentage of observations using both sugarcane ethanol and biodiesel to meet the other advanced mandate. ³Brazilian domestic wholesale anhydrous ethanol price, with exchange rate at 2.05 reals per dollar.

Table 7 Market Effects of U.S. Corn Yield

U.S. Corn Yield	143.8 bu/ac	162.9 bu/ac	176.3 bu/ac
Percentage with Two-way Trade ¹	0.4	1	1
Percentage using both fuels ²	0.67	0.04	0.09
Corn Price (\$/bushel)	6.83	4.73	4.71
U.S. Ethanol Plant Price (\$/gallon)	2.53	1.98	1.97
Brazil Ethanol Price ³ (\$/gallon)	2.79	2.36	2.35
Soybean Price (\$/bushel)	9.97	8.34	8.15
Soybean Oil Price (cents/pound)	61.26	56.12	55.93
Soybean Meals Price (\$/short ton)	263.49	229.54	224.09
U.S. Ethanol Production (BG)	14.32	15.69	15.77
U.S. Ethanol Exports (BG)	0.12	1.65	1.65
U.S. Ethanol Imports (BG)	1.26	1.49	1.47
Conventional RIN Price (\$/gallon)	1.22	0.69	0.69
Biodiesel RIN Price (\$/gallon)	1.91	1.73	1.72
Advanced RIN Price (\$/gallon)	1.86	1.45	1.45

Note: All results are reported in the regular units in the market. All RIN prices are in ethanol equivalent unit. ¹Percentage of observations with the U.S. exporting corn ethanol to Brazil, and importing sugarcane ethanol from Brazil simultaneously.

²Percentage of observations using both sugarcane ethanol and biodiesel to meet the other advanced mandate. ³Brazilian domestic wholesale anhydrous ethanol price, with exchange rate at 2.05 reals per dollar.