Welfare Assessment of the Renewable Fuel Standard: Economic Efficiency, Rebound Effect, and Policy Interaction in a General Equilibrium Framework

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1. Introduction

The USA Energy Independence and Security Act of 2007 (RFS2) defined mandatory annual targets to increase consumption of conventional, advanced, and cellulosic biofuels until 2022. The cellulosic component of the RFS has largely been waived up to date, but not the other categories. The annual volumetric targets for corn ethanol have been achieved, and the industry is expected to reach the target of 15 billion gallons of ethanol production prior to 2015. The economic and environmental consequences of this rapid expansion have been the focal point of many studies in recent years. These studies have used partial and general equilibrium economic models and analyzed the price impacts, welfare consequences, displacement between gasoline and ethanol consumption (rebound effect), induced land use changes, and reduction in emissions due to ethanol expansion. Most of partial equilibrium models developed in these analyses captured only the interactions between the energy and agricultural markets and ignored other economic activities and the fact that economic resources are limited. In addition, these studies failed to fully capture the interactions between the biofuel mandates and other existing distortionary tax policies. The general equilibrium analyses have taken into account the interactions between the agricultural, energy and other economic activities and considered the exiting resource constraints in their economic assessments of biofuel polices. However, like the partial equilibrium analyses, they ignored the fact that biofuel policies and other distortionary taxes interact, and these interactions could alter the economic implications of biofuel mandates.

In general, there are two approaches to stimulate biofuel production: taxes/subsidies or mandates. The government could use economic incentives such as tax policies to encourage producers and/or consumers to produce and consume more biofuels. In this approach, the economy will pay the costs of policy through the tax system, and the burden of the policy depends on the efficiency of the tax system and the type of tax incentives. As an alternative the government can mandate biofuels and define penalties to force the economy to produce/consume the mandated level. In both cases the burden of the policy will be divided between the consumers, blenders, and gasoline, corn, and biofuel producers. However how the cost ends up being absorbed can change from one option to another. To examine the economic consequences of a biofuel subsidy or mandate policy we need to recognize how the policy is implemented in practice.

The US government has used a combination of these policies to boost ethanol production. The government has announced annual targets for corn ethanol with a maximum of 15 billion gallons which is slated for 2015 and will stay at that level thereafter. To force the market to produce the mandated target the obligated parties (the blenders) are fined if the target is not achieved. In addition, the government was paying a tax credit to the blenders per gallon of ethanol, and an ethanol tariff was in place too. These two policy provisions expired at the end of 2011. While many studies have examined these policies, the fact that these policies interact with other exiting policies is ignored. The implemented biofuel policies have raised the price of agricultural commodities and hence reduced the need for agricultural subsidies. The commodity subsides paid in 2000 were more than $20 billion. This figure was about $6 billion in 2010. Hence, we can expect that the reductions in agricultural subsidies relieved a portion of the burden of the ethanol subsidy policy. On the other hand, the mandate has forced the blenders to mix ethanol with gasoline. Over the past decade the wholesale price of ethanol (gasoline equivalent) was significantly higher than the wholesale price of pure gasoline (see figure 1). This means that the price of the blended fuel was higher in cost than pure gasoline, and the economy has paid the higher price due to the mandate. One can consider the difference between the prices of gasoline and ethanol (gasoline equivalent) as an implicit tax on the blended fuel. Of course consumers and producers shared the burden of this implicit tax. To correctly assess the economic impacts of the ethanol policy the explicit and implicit component of this policy and the interplay between the mandate and other exiting tax policies should be recognized and taken into account.

This paper develops analytical and numerical general equilibrium models to examine the importance of the implicit and explicit portions of the USA ethanol policy and their interactions with other pre-exiting distortionary policies (such as agricultural or income taxes) for the economic analyses of this policy. In this paper we first develop a stylized analytical general equilibrium framework which represents interactions between economic activities and government policies in a simple economy. The stylized analytical model is developed based on the work done by Goulder et al. (1999) and Taheripour et al. (2008). The first paper examined the cost effectiveness of alternative air pollution reduction policies in a second-best setting, and the second paper analyzed welfare impacts of alternative polices for agricultural pollution control again in a second best setting. The analytical work decomposes the welfare impacts of a representative mandate policy into several components and shows how they affect welfare and interact with the implemented policy. The analytical work also indicates how the economy substitutes ethanol with gasoline and examines under what conditions the mandate could induce a rebound effect. Then we use a computable general equilibrium model to quantify the economic impacts of the US ethanol policy. For the numerical analyses we rely on the GTAP-BIO-ADV model developed by Taheripour, Tyner, and Wang (2011).

2. Literature Review

The economic and environmental consequences of the US ethanol mandate have been examined from different angles using a wide range of economic modeling approaches. Many papers have used partial equilibrium models and highlighted the economic implications of this policy for the US economy. Early studies in this area examined the role of ethanol as an additive to gasoline and argued that using ethanol as an alternative for MTBE (another oxygenate) could increase economic welfare and reduce emissions (for example see Gallagher et al. 2003). Several papers examined the importance of government fixed ethanol subsidy for agricultural and energy markets and its economic consequences. In this context Gardner (2007) examined the choice between crop and ethanol subsidies and claimed that a deficiency payment program (a direct subsidy to corn producers) that costs the same to tax payer as ethanol subsidy will induce an annual deadweight losses of $37 million in long run. His corresponding estimate for the deadweight loss of ethanol subsidy was about $665 million. He missed the fact that an increase in ethanol subsidy could reduce the need for agricultural subsidies. Tyner and Quear (2006) and Tyner and Taheripour (2007) showed that replacing the fixed per gallon ethanol subsidy with a variable-rate subsidy could reduce the social costs of the government intervention and still protect the ethanol industry from the adverse consequences of down ward shifts in crude price. Taheripour and Tyner (2007) and de Gorter and Just (2007) studied the efficiency and distributive effects of a biofuel subsidy. Rajagopal et al. (2007) argued that the ethanol tax credit reduces the price of gasoline by 3% and could improve the welfare of the US economy by $11 billion. On the other hand, de Gorter and Just (2009) showed that in the presence of farm subsidies the ethanol tax credit will reduce the welfare of the US economy by $1.3 billion.

In another line of research several papers examined the implications of ethanol subsidy for fuel demand. These papers usually employed partial equilibrium models and to argue that the ethanol subsidy could reduce the price E10 and raise the demand for this product. These papers claim that the increased demand for E10 due to the ethanol subsidy may mitigate environmental and security benefits of ethanol production because the subsidy generates a rebound effect which eventually leads to higher demand for gasoline and more imports of crude oil (for example: see Vedenov and Wetzstein, (2007) and Khanna et al., (2008)). Several papers also examined the effect of ethanol mandate on gasoline demand. For example, de Gorter and Just (2008) examine the effects of a tax credit in the presence of a blend mandate. They showed that a tax credit with a mandate results in a subsidy to fuel consumers and higher fuel consumption. Hochman et al. (2010) also claimed that introducing biofuels into the energy market generates a rebound effect at a global scale.

Almost of the analyses mentioned above are based on partial equilibrium models, which manly highlighted consequences of the US ethanol policy for agricultural and/or fuel markets. These analyses usually ignore the rest of the economy and disregard the fact that resources are limited and that the biofuel mandates interact with other policies and pre-existing distortionary taxes.

By the second half of the 2007, the importance of indirect land use emissions induced by biofuel production were introduced in to the literature. The early papers in this field suggested that biofuel production could have extraordinary land use implications (Tokgoz et al., 2007; Kammen et al., 2007; Searchinger et al., 2008; Fargione et al., 2008). For example, Searchinger et al. (2008) provided the first peer-reviewed estimate for the ILUC (about 0.73 hectares of new cropland area per 1000 gallon of ethanol capacity). Those authors used a partial equilibrium modeling framework (FAPRI) to assess the ILUC due to US ethanol program. However, the more recent studies find the early estimates have overstated the land use implications of US ethanol production (Hertel et al., 2010; Al-Riffai et al., 2010; EPA, 2010; Taheripour et al., 2010; Tyner et al., 2010; and Laborde, 2011). For example, Hertel et al. (2010) using a general equilibrium model showed that full accounting for market mediated price responses to ethanol production, as well as the geography of world trade, contributed to significant reductions in estimated ILUC impacts. Those authors estimated that the ILUC for the US ethanol program is about 0.29 hectares per 1000 gallons of ethanol.

Almost all research studies which examined the induced land use changes also ignored the that the US ethanol policy has reduced the need for agricultural subsidies and their experiments poorly represent the way that the policy is implements in real world. In this paper we show that including reduction in agricultural production subsidies could significantly alter the induced land use changes due to ethanol production.

3. Why Simple Partial Equilibrium Models Could Be Misleading

In this section we employ a simple partial equilibrium model which has been frequently used to assess the welfare impacts of biofuel policies. In this analysis it is assumed that gasoline and ethanol are perfect substitutes and they have identical energy contents. Consider the left panel of Figure 2 which represents the market for ethanol. In this market the supply of and demand for ethanol with no government intervention are shown with S_{e0} and D_e. The demand curve for ethanol represents the derived demand of the blender which blends ethanol with gasoline at an arbitrary rate and supplies the blend to the market for the blended fuel. This figure assumes that with no government support, ethanol production is zero. This means that the marginal cost of ethanol production is higher than the blender’s willingness to pay for ethanol at any production level of this fuel. Now assume that the government subsidizes ethanol production with a fixed rate of t_e per gallon of ethanol. Ignore the fact that the government needs to finance the policy. In this partial equilibrium framework the supply of ethanol will shift to S_{e1}. With this subsidy the equilibrium price and quantity of ethanol will be p_{e1} and Q_{Se1} . At this equilibrium the ethanol producer receives p_e per gallon of ethanol and the blender pays p_{e1} per gallon. With this set up the change in benefits received by the ethanol producer, the change in benefits received by the blender, and the amounts of subsidy paid by the government are equal to the areas of a, b, and $a+b+c$, respectively. The deadweight losses observed due to the ethanol subsidy would be equal to c[1]. Now for a moment assume that the policy has no other welfare impacts. With this assumption in mind now consider the right panel of Figure 2 which depicts the market for the blended fuel. Given that the market for pure ethanol (say E85) is negligible we assumed that the consumers only consume the blended fuel and that the curve D_b represents their demand curve for this product. When ethanol is not subsidized the supply curve of $S_b = S_g + S_{e0}$ represents the market supply. With this supply curve the market equilibrium for the blend would be at E_0 with no ethanol blended with gasoline. When the government pays ethanol subsidy then the curve $S_b = S_g + S_{e1}$ represents the supply curve of the blend and the market equilibrium for the blended fuel moves to E_1. At this equilibrium supplies of gasoline, ethanol, and the blended fuel would be equal to O_bQ_g, $O_eQ_{Se1}=Q_gQ_1$, and O_bQ_1, respectively. In this situation one can conclude that the ethanol subsidy creates a rebound effect because it increases the consumption of the blended fuel by Q_oQ_1.

We now take into account the fact that the government needs to finance the ethanol subsidy. There are several ways to finance the policy. Reduction in existing subsidies, an additional fuel tax on gasoline production, an income tax, and or changing in tax rates imposed

[1] The deadweight losses mention here belongs to changes in ethanol market. Ethanol subsidy could affect consumers and producers surpluses in other markets as well. A partial equilibrium model can trace the changes in consumers and producers surpluses in few other markets such as markets for corn and E10, but they fail to capture the welfare impacts through the entire economy.

on other goods and services are some options to finance the ethanol subsidy. Using either of these options or a combination of them will affect the above partial equilibrium analyses. To examine how the financing issue could alter the above rebound effect conclusion, consider a simple income tax. The income tax shrinks the households' disposable incomes which eventually reduces demands for goods and services including the demand for fuel. Consider now a case where the income elasticity of demand for fuel is high and the income tax hits the demand for this commodity significantly. The left panel of Figure 3 represents this situation. This figure indicates that if the induced income tax effect of the ethanol subsidy is high, then the demand curve for ethanol shifts back significantly and no rebound effect is observed in the new equilibrium of E1 where $Q_1<Q_0$. On the other hand, if the income elasticity of the demand for fuel is low, then the demand shifts back slightly and results in a minor rebound effect (see the right panel of figure 3). This simple example shows that including the possibility of an income tax for supporting the ethanol subsidy could alter the results of our partial equilibrium analyses. In general, studies which argued for rebound effect used partial equilibrium models which ignore the fact that the ethanol subsidy needs to be financed through the tax system.

Consider now a case where the government does not pay any subsidy but forces a fuel blend including a certain share of ethanol per gallon of the blend, say α. Given that the price of ethanol is more expensive than the price of gasoline we can assume that: $p_e=(1+\beta)p_g$. Here p_e and p_g represent the prices of ethanol and gasoline, respectively, and $\beta>0$. Following an average pricing rule the supply price of the blend will be: $p_b=(1+\mu)p_g$ where $\mu=\beta(1-\alpha)>0$. Hence, in this case the blending mandate increases the supply price of the fuel with an equivalent ad valorem rate of $\mu=\beta(1-\alpha)>0$. The left panel of Figure 4 represents the supply curve of the blended fuel for this case with S_b. In this panel the market equilibrium is at E_1 with the equilibrium price of p_b

(higher than the initial price of p_0) and the equilibrium quantity of Q_b (less than the initial quantity of Q_0). With a blending mandate in place the ethanol producer receives p_e and the gasoline price received by gasoline producer is p_g. As shown in the right panel of figure 4 the difference between these two prices represents the social costs of the mandate per gallon of produced ethanol. In this case the partial equilibrium analysis does not produce a rebound effect because the price paid by the consumer of the blended fuel increases due to the mandate. However, it shows that the price received by the gasoline producer drops from p_0 to p_g and the quantity of gasoline supply falls from Q_0 to Q_g. The reduction in gasoline price received by the gasoline producer with reduction in gasoline consumption in a country with mandate can open the room for other countries to expand their gasoline consumption and that could lead to a rebound effect at the global scale. The global numerical general equilibrium analysis provided in this paper indicates that the US ethanol mandate causes a week rebound effect at the global scale.

The above partial equilibrium analysis showed that imposing a mandate could not cause a rebound effect in the country which imposes the mandate. This could be a misleading conclusion. For example, in the US case the ethanol mandate could lead to increases in crop prices, raise farmers' incomes, increase land prices, generate higher income from trade of commodities, reduction in agricultural subsidies, and cause many other impacts. The compound effect of these changes could alter our conclusion from the above partial equilibrium analysis.

4. An Analytical General Equilibrium Framework

The analytical model developed in this section follows the work done by Goulder et al. (1999). These authors employed a stylized analytical general equilibrium framework and examined the cost effectiveness of alternative air emissions reduction policies in the presence of pre-existing distortionary labor tax. Taheripour et al. (2008) extended their work and examined the economic efficiency of agricultural pollution reduction policies in the presence of labor and agricultural support policies. We revise this model by introducing ethanol into the modeling structure.

Consider an open economy with three commodities - gasoline (X), ethanol (E), and food (Y) with constant returns to scale production technologies. Gasoline consumption generates two externality costs. It increases emissions and reduces national security. The per gallon social costs of gasoline consumption are ω. The economy consists of three producers each producing only one commodity; a representative consumer who consumes good and services and owns endowments including labor ($\bar{L}$), land ($\bar{R}$), and capital ($\bar{K}$); and a government which determines income tax rates on labor (t_L), land (t_R), and capital (t_K), regulates externality costs of gasoline using a fixed tax rate (t_X) per gallon of produced gasoline, supports food production using a production subsidy (S_E), regulates imports of gasoline to match the world price of gasoline with its domestic market price using a tariff rate of t_m on imported gasoline, and pays transfer payments (G). The representative consumer derives utility from consumption of gasoline (C_X), Ethanol (C_E), Food (C_Y), and leisure (l) and disutility from gasoline externality costs ($\dot{I}$) through the following utility function:

$$u = u(C_X, C_E, C_Y, l) - \phi(\dot{I}\ ). \qquad (1)$$

Here $l = \bar{L} - L$, where L represents labor supply. The consumer receives disposable income from work ($(1-t_L)L$: wage is the numeraire and hence equals one) and non-labor income (Q) including capital income ($(1-t_K)r_K\bar{K}$: r_K represents price of capital), land income ($(1-t_R)r_R\bar{R}$: r_R represents price of land), and government transfer payments (G: no tax on transfer payments). The consumer allocates this income to purchase gasoline (C_X), Ethanol (C_E), and (C_Y) with market prices of p_X, p_E, and p_Y, respectively. Hence the consumer budget constraint is:

$$p_X C_X + p_E C_E + p_Y C_Y = (1 - t_L) L + Q. \quad (2)$$

The economy is competitive, exports (*y*) some part of food production, and imports (*x*) some part of its gasoline consumption. The economy imports gasoline (the dirty good) at the world price (p_{XW}) and exports food at domestic market price (p_Y). The trade is in balance as shown in the following:

$$p_{XW} x = p_Y y(p_Y). \quad (3)$$

Here $p_{XW}=p_X-t_m$, where t_m stands for any difference between the domestic and world prices of gasoline, which implies a tariff/subsidy per unit of imported gasoline.

In this economy producers use Constant Returns to Scale (CRS) technologies. This implies zero profits in production process of gasoline, ethanol, and food in a competitive market zero profit condition. Under these assumptions the marginal and average costs are equal to each other in the absence of regulation. These assumptions in combination with the existing regulations introduced above imply:

$$p_X = MC_X(r_R, r_K) + t_X, \quad (4)$$

$$p_E = MC_E(r_R, r_K) - S_E, \quad (5)$$

$$p_Y = MC_Y(r_R, r_K) - S_Y. \quad (6)$$

Finally, with the assumptions and the regulations defined above, the government budget constraint can be defined in as follow.

$$t_X O_X + x(t_m) + t_L L + t_R r_R \bar{R} + t_K r_K \bar{K} = s_E O_E + s_Y O_Y + G. \quad (7)$$

Here O_X, O_E, and O_Y represent outputs of gasoline, ethanol, and food. In this equation the first two elements of the left hand side show revenues from production and imports of gasoline. Other components of the left hand side measure revenues from income taxes. The right hand side of the government constraint measures government's payments to support ethanol and food production and transfer payments.

In order to reduce emissions caused by gasoline consumption the government has several options to follow in this simple economy. Some important options are: an increase in gasoline tax, an increase in ethanol subsidy, a mandate on gasoline consumption or production, a mandate on ethanol consumption or production, introducing a tax on emissions, introducing an emissions reduction subsidy, and/or a combination of these policies. These policies could induce different welfare impacts and affect the economy in different ways. Given that the US has in the past used an ethanol tax credit, we examine the welfare impacts of an increase in ethanol subsidy to reduce total externality costs of gasoline consumption ($I = \omega C_Y$).

To achieve this goal consider a marginal increase in ethanol subsidy. To finance this policy the government can increase income tax rates, reduce food subsidies, change gasoline tariff rate, reduce transfer payments, or a combinations of these methods. To assess a general case assume that all of these options are all on the table.

To determine the welfare impacts of a marginal increase in ethanol subsidy in a general case, we differentiate the utility function with respect to S_E, enforce the household budget constraint, impose the trade balance, take into account the government budget constraint, apply the market clearing condition, and use Slutsky equation and Shepard's lemma and several other microeconomic theories[2]. The welfare impacts are classified into several components and are shown in the following equation:

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[2] A similar approach is used in Goulder et al. (1999) and Taheripour et al. (2008). The decomposition process used in this paper is available upon request from the authors.

$$
\frac{du}{\lambda ds_E} = \underbrace{-s_Y \frac{dO_Y}{ds_E}}_{\text{Primary food effect}} \underbrace{+t_m\left(O_X + x\right)\varepsilon_X\theta_X - s_E O_E \varepsilon_E \theta_E}_{\text{Primary Rebound Effect}}
$$

$$
\underbrace{-(1+\varepsilon_x)\frac{dp_X}{ds_E}x + p_X\frac{dx}{ds_E} + (1-\varepsilon_y)\frac{dp_Y}{ds_E}y + p_Y\frac{dy}{ds_E} + x\frac{dt_m}{ds_E}}_{\text{Primary Trade Effect}} \qquad (8)
$$

$$
\underbrace{+M\left(\frac{dI_{LTR}}{ds_E}\right)}_{\text{Revenue Recycling Effect}} \underbrace{-\sum_{J=X,E,Y}\left(\tau t_L\left(-\frac{\partial L}{\partial p_J}\right) + \tau'(C_J)S_G\right)\frac{dp_J}{ds_E}}_{\text{Tax Interaction Effect}} \underbrace{+\tau t_L \varepsilon_{LQ}\left(\frac{L}{Q}\right)\left(\frac{dQ}{dt_I} - \frac{dG}{dt_I}\right)}_{\text{Non-Labor Income Effect}}.
$$

The first three components measure the primary impacts of an increase in ethanol subsidy. The primary food effect is expected to be welfare improving. An increase in ethanol subsidy moves resources away from food to ethanol production and reduces the need for food subsidy. This item shows only the direct efficiency gain due to reduction in food subsidy. The second terms measures the impact of rebound effect on welfare. In this component θ_X and θ_E show percentage changes in consumption of gasoline and ethanol, and ε_X and ε_E stand for the demand price elasticities of these commodities. This component could increase or decrease welfare. In this component $-s_E O_E \varepsilon_E \theta_E$ is always welfare improving. However, $t_m\left(O_X + x\right)\varepsilon_X\theta_X$ could be positive or negative. The percentage change in gasoline consumption, θ_X, determines the sign of this subcomponent. If θ_X <0, then this subcomponent is positive and hence the overall primary rebound effect is welfare improving. However, if θ_X >0, then the welfare impact of primary rebound effect could be positive, negative, or zero.

The next component is the primary trade effect. In general, when the demand for the exported food is inelastic, the world price of gasoline remains constant (or goes down), and the tariff (t_m) remains unchanged, then the trade effect will be welfare improving. Otherwise it could be either positive, negative or zero.

The next component in equation 8 shows the revenue recycling effect. If the ethanol subsidy is financed using a labor tax, then the revenue recycling effect would be welfare decreasing. The next component is labeled tax interaction effect. The tax interaction effect measures efficiency costs due to interaction between the ethanol and labor tax. This secondary effect could be either positive or negative. Finally, the last component of the above equation measures efficiency costs due to interaction between labor supply and non-labor incomes. The policy will likely increase the price of land, which leads to an increase in leisure and reduces labor supply. This will reduce welfare. For more detail about the last three components of equation (8) see Taheripour et al. (2008).

We now analyze the consequences of the ethanol subsidy for the substitution between gasoline and ethanol. Using the budget constraint defined in equation (2) in combination with some standard derivations it is straightforward to show that:

$$\frac{dC_X}{dC_E} = -\frac{1}{\varepsilon_{EX}}\frac{C_X}{C_E} - \left(\frac{\varepsilon_Y + 1}{\varepsilon_{YE}}\right)\frac{C_Y}{C_E}\frac{p_Y}{p_X} + \left(\frac{\alpha_E}{\varepsilon_{IE}} - \frac{1+\varepsilon_E}{\varepsilon_E}\right)\frac{p_E}{p_X}. \qquad (9)$$

In the derivation process of this equation, it is assumed the government does not increase income tax rates to support the ethanol subsidy. This equation indicates that the displacement ratio between gasoline and ethanol (dC_X/dC_E) is a function of own and cross price elasticities, relative prices, and relative consumption of commodities. This ratio measures rebound effect according to the following chart:

- If $dC_X/dC_E \geq 0$, then an increase in ethanol consumption due to an increase ethanol consumption does not reduce consumption of gasoline. In this case total consumption of fuel (C_X+C_E) goes up by (dC_E+dC_X: where $dC_X \geq 0$). We refer to this as *strong rebound effect*.

- If $0 > dC_X/dC_E > -1$, then an increase in ethanol consumption due to an increase in ethanol subsidy decreases consumption of gasoline with an amount less than the increase in ethanol production. In this case total consumption of fuel (C_X+C_E) goes up by (dC_E+dC_X: where $dC_X < 0$). We refer to this as *weak rebound effect*.
- If $dC_X/dC_E \leq -1$, then an increase in ethanol consumption due to an increase in ethanol subsidy decreases consumption of gasoline with an amount equal or larger than the increase in ethanol production. In this case total consumption of fuel (C_X+C_E) goes down or stays the same. We refer to this case as no rebound effect.

Since ethanol is a substitute for gasoline, then $\varepsilon_{EX} > 0$, and hence the first term in equation (8) is always negative. Consider the sign of the next two components of this equation. If food and fuel (ethanol) are compliments, then $\varepsilon_{YE} < 0$. Therefore, with an inelastic food demand the second term is positive. Finally, if the income elasticity of demand for ethanol is positive, and its own price elasticity is less than one then the third term is positive too. With these assumptions the displacement ratio can be either positive or negative. Hence in general an ethanol subsidy may or may not generate a rebound effect. In general we can conclude that:

From the above analysis it clear that if ethanol and gasoline are compliments then the first component of equation (8) will become positive. The combination of this assumption and other assumptions on the income and price elasticities noted above implies a strong rebound effect. This means that if ethanol is an additive for gasoline, then it is likely to observe a strong rebound effect due to the ethanol subsidy.

5. Numerical Model

To evaluate the economic impacts of the US ethanol policy we modify the GTAP-BIO-ADV model developed in Taheripour, Tyner, and Wang (2011)[3]. This model is designed and used to assess the land use impacts of alternative biofuel pathways. The GTAP-BIO-ADV is a CGE mode which takes into account the interactions between a wide range of economic activities (including biofuels) and handles production, consumption, and trade of goods and services at a global scale, while it allocates scarce resources such as land, labor and capital among economic activities. This model covers production and consumption of the first and second generation of biofuels and links them with other industries and services.

This model includes the traditional fuels markets as well. The oil, gas, and coal industries supply materials to the processed petroleum, electricity, and other industries at the global scale. In general, the model considers liquid biofuels (ethanol, biodiesel, and bio-gasoline), as direct substitutes for gasoline. However, it assumes low degrees of substitutions among all energy commodities at the firm and household levels as well.

The model takes into account the competition for land among the land use industries such as forestry, livestock, and crop industries. Production of biofuel (except for corn stover) increases competition for land among the land use industries. In this model cropland pasture is a part of cropland and is an input in the production processes of the livestock industry.

The model handles the production, consumption, and trade of a wide range of commodities at a global scale. It aggregates the world economy into 43 groups of commodities

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[3] The model is an advanced version of GTAP-BIO model which developed by Taheripour et al. (2010), Hertel, Tyner, and Birur (2010), and Taheripour, Hertel, and Tyner (2011) and Tyner et al. (2011).

(including biofuels, DDGS, and oilseed meals) and 19 regions and represents the world economy in 2004.

The GTAP-BIO model and its successors substitute ethanol and gasoline volumetrically. Given that the energy content of ethanol is about 67% of gasoline, the volumetric approach could generate misleading results. To fix this problem we made proper changes in the model to compare ethanol and gasoline based on their energy contents. We use the modified GTAP-BIO_AEZ model to examine the economic impacts of the USA ethanol mandate.

The RFS2 is the core component of the US ethanol policy. This mandate forces the economy to consume 15 billion gallons of corn ethanol in 2015. At the same time the mandate has been supported by an ethanol tax credit and a trade tariff until the end of 2011. We can consider reduction in agricultural subsidy as a portion of ethanol policy as well. To introduce all components of the ethanol policy into the GTAP simulation process we have several options to follow. Consider the following three options.

Option 1

To implement the mandate and enforce the market to produce and consume 15 billion gallons of ethanol we need to introduce a market incentive into the GTAP-BIO-AEZ Model. The market incentive could be a revenue neutral tax credit for ethanol production financed by a gasoline tax. This method imposes the main burden of the policy on parties involved in fuel market (ethanol producer, refineries, and fuel consumers). This method does not simulate the actual ethanol policy, but measures the economic impacts if we ignore other components of the policy. This method constitutes our first simulation. We refer to this simulation as *experiment I.*

Option 2

This option brings reduction in agricultural production subsidy into account. We know that in reality ethanol production has decreased the need for agricultural production subsidies. The GTAP model uses ad valorem subsidies and thus cannot adjust them as commodity prices increase However, many tax rates are flexible in real world. For example, the US production subsidies go down if crop prices go up. We fixed this problem in option 2 by reducing US agricultural production output subsidies to zero, while other agricultural subsidies remain in effect according to their 2004 rates presented in the base data. In this option a portion of required ethanol subsidy comes from reduction in agricultural subsidy, and as a result, a lower gasoline tax is required to achieve the mandated level of 15 billion gallons of ethanol. We refer to this simulation as *experiment II*.

Option 3

Options 1 and 2 mainly impose the burden of the mandate policy on fuel market. In option 3 we assume that the government cuts agricultural production subsidies, and then finances the rest of required ethanol subsidies to produce 15 billion gallons of ethanol using an income tax increase. This method spreads the burden of the mandate to all economic activities. We refer to this option as *experiment III*.

In conclusion the above experiments can be defined as:

Experiment I: An increase in USA ethanol production from its 3.41 billion gallons in 2004 to 15 billion gallons mandated for 2015 using an incentive production subsidy per gallon of ethanol financed using a gasoline production tax.

Experiment II: An increase in USA ethanol production from its 3.41 billion gallons in 2004 to 15 billion gallons mandated for 2015 using a production subsidy per gallon of ethanol financed using a gasoline production tax and by reduction of US agricultural subsidies to zero.

Experiment III: An increase in USA ethanol production from its 3.41 billion gallons in 2004 to 15 billion gallons mandated for 2015 using a production subsidy per gallon of ethanol financed using a an income tax and by reduction of US agricultural subsidies to zero.

6. Numerical Results

The numerical analyses provide in this section are all based on the results obtained from the experiments introduced in the previous sections. The numerical analyses cover impacts of the ethanol mandate on commodity prices, crude oil and gasoline prices, fuel production, trade balance, and welfare.

Price impacts

The ethanol mandate increases market prices of crop commodities. Among the alternative options, experiment *I* generates the lowest impact on crop prices. This is because this experiment assumes that agricultural activities will continue to receive production subsidies in the presence of the ethanol mandate. The crop price impacts obtained from experiments *II* and *III* are very similar and significantly higher than the price impacts of experiment *I*. For example, experiments *I*, *II*, and *III* predict that the ethanol mandate increases the price of coarse grains by about 7.2%, 16.9%, and 16.8% respectively.

On the other hand experiment *I* predicts the highest price impact for gasoline and crude oil, because this experiment ignores the fact that a portion of required subsidy for ethanol is financed due to reduction in agricultural subsidies. On the other hand, experiment *III* predicts the lowest price impact for gasoline, because it spread the burden of the policy on all economic actives and finances a portion of the required subsidy by reduction in agricultural subsides. Indeed experiment *III* shows that if the mandate is supported by an income that, then it could reduce the price of gasoline. The real world functioning of the ethanol mandate may be somewhere between experiments II and III (with no explicit ethanol subsidy in effect after 2011, most likely closer to experiment II). Thus the impact of the ethanol mandate on the price of gasoline ranges somewhere between a reduction of 1.6% to an increase of 4.3%. The bottom line is that the impact of the ethanol subsidy on the gasoline price is small. Finally, all experiments show that the ethanol mandate barely reduces the crude oil price (by a number between -1.2% to -2.9%).

Impact on fuel production and rebound effect

An increase in US ethanol production from its 3.41 billion gallons in 2004 to 15 billion gallons increases the supply of ethanol by 11.59 billion gallons. This is identical to 7.77 billion gallons of gasoline and is not a large number compared to the global energy market. However, it is large enough to affect the US gasoline market. The impacts adding 7.77 billion gallons of ethanol gasoline equivalent (EGA) on the US and world gasoline market are shown in table 2. This table shows that the ethanol mandate reduces US gasoline consumption by about 11.44 billion gallons if we put the burden of the mandate on the fuel market and ignore reduction in agricultural subsidy as shown in experiment *I*. When we bring reduction in agricultural subsidy into account, the mandate reduces US gasoline consumption by 11.49 billion gallons in experiment *II*. Finally, in experiment III when we spread the burden of the mandate among all economic activities and take into account reduction in agricultural subsidies, then mandate only reduces gasoline consumption by 8.06 billion gallons. Indeed experiment *III* is the most efficient policy and has the lowest economic burden. In this case the reduction in gasoline consumption and the increase in EGA are close to each other. Table 2 shows that the mandate does not generate any rebound effect in the USA.

The US biofuel mandate reduces global gasoline consumption lees than the expected reduction in US under all policy settings. In experiment III, the mandate causes a rebound effect at the global scale. The global price of gasoline goes down and that encourages some countries to increase their gasoline consumption. In this case in response to an increase in EGA by 7.77 billion gallon, the global consumption of gasoline decreases only by 5.92 billion gallons.

Trade impacts

Table 3 shows that the ethanol mandate generates a positive trade balance of $1.323 billion in experiment *I* which induces a sharp reduction in USA gasoline consumption (table 3). In experiments *II* and *III*, the mandate generates negative trade balance of $-1.034 billion and $-5.018 billion. Table 3 indicates that USA biofuel mandate can affect the trade balances of other counties as well. The regional impacts are not the same across the examined experiment.

Welfare impacts

Finally, consider the welfare impacts in Table 4. As shown in this table the ethanol mandate reduces welfare under all experiments. The first experiment represents the worst case which causes about $16.8 billion in welfare losses. The second and third experiments generate about $15.3 billion and $14.8 billion welfare losses, respectively. Hence experiment *III* which considers reduction in agricultural subsidies and implements revenue neutral tax on gasoline financed using an income tax is the least cost policy. The overall global welfare impact of the USA ethanol mandate does not very significantly with the alternative policy set ups defined in experiments *I*, *II*, and *III*. However, regional impacts vary from one experiment to another one in each region.

Land use impacts

The induced land use impacts due to ethanol production have been the focal point several studies in recent years. Figure 5 represents impacts of ethanol production on expansion in cropland by region. In general, this figure shows that reduction in US agricultural production subsidies reduces the global cropland expansion due to ethanol production from about 2 million hectares in experiment I to about 1.9 million hectares in experiments *II* and *III*. This figure also shows that reduction in US agricultural production subsidies shifts the induced land use impacts of ethanol production from US to other regions. The expansion in US cropland is close to 1 million hectares in experiment I. This figure falls to about 0.3 million hectares in experiments II and III. This substantial difference means ignoring the fact that ethanol production reduces the need for agricultural subsidies leads to misleading estimates for induced land use changes due to ethanol policy.

7. Conclusion

In this paper, we have shown that partial equilibrium evaluations of biofuels policies can lead to misleading results. We then develop a stylized theoretical model to show how a general equilibrium setup can improve the analysis of price, welfare, rebound, and other impacts. Finally, we implement an empirical analysis of the US corn ethanol mandate and show that inclusion of agricultural subsidies and income tax impacts are very important. For example, previous work (including our own) has seriously underestimated the price impacts on coarse grains because the financing of the implicit subsidy did not consider the reduction of agricultural subsidies. Also, other studies in the literature have estimated huge gasoline price decreases due to the US ethanol program. Here, we show that the gasoline price impact is essentially zero. These other studies did not include all the economy wide impacts. We also show the rebound, trade, and welfare impacts of the policy cases. The welfare impacts, interestingly, do not differ significantly across the cases.

We also show that ignoring the reduction of agricultural output subsidies due to higher coarse grain prices induced by biofuels demand leads to very misleading geographical distribution of land use changes. Taking into account the agricultural subsidy reduction diminishes land use change in the US by about 70%, while reducing global land use change only about 5%.

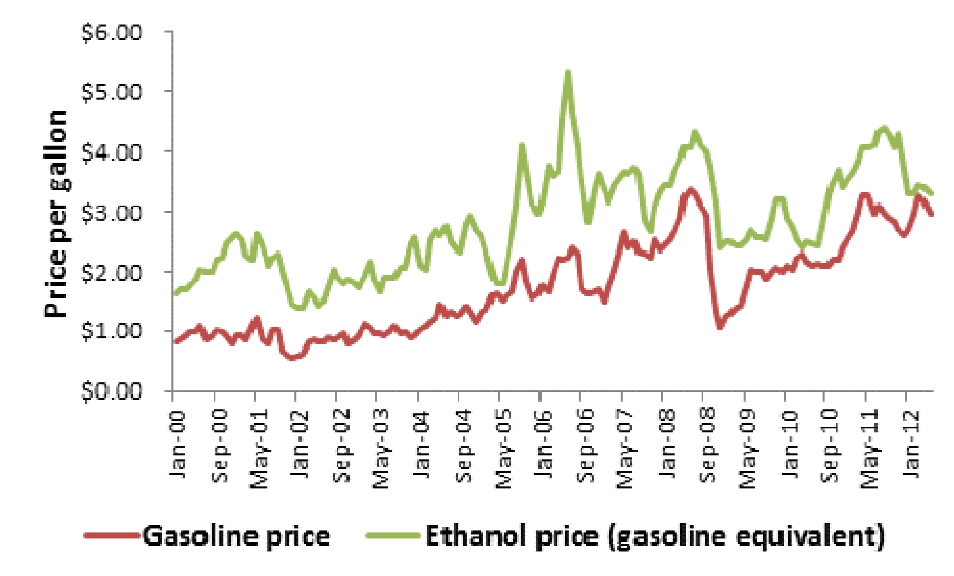

Figure 1. Ethanol and unleaded gasoline average rack prices

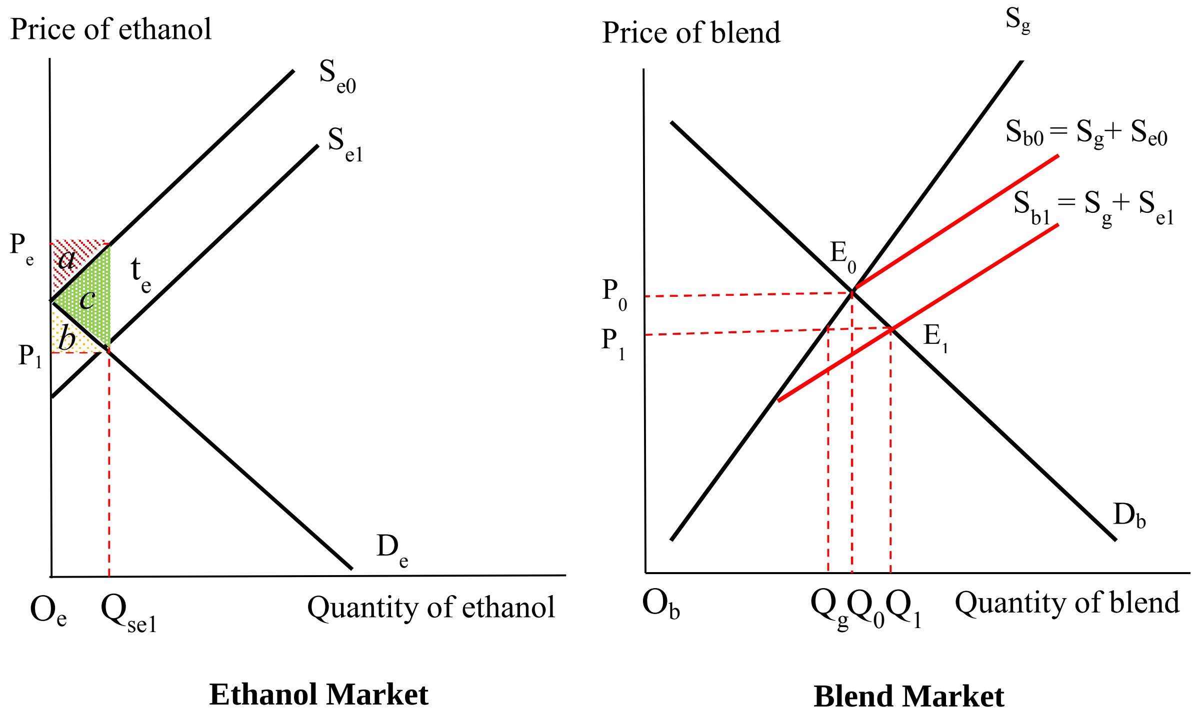

Figure 2. Impacts of an ethanol subsidy on fuel market

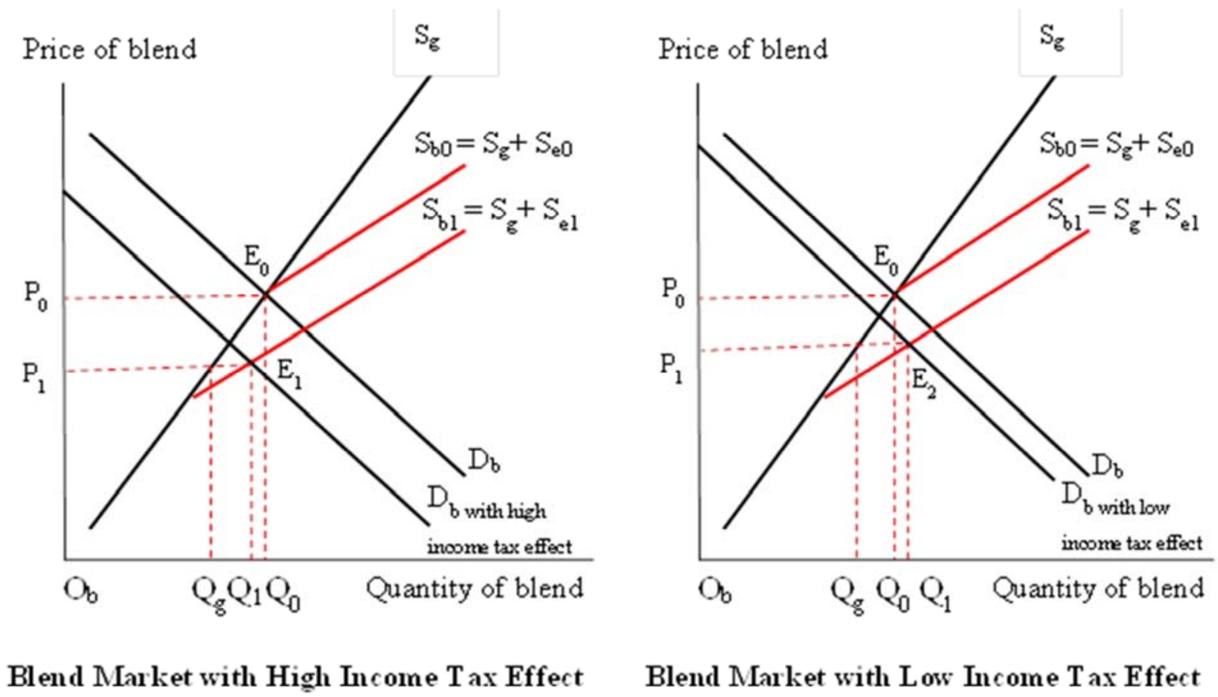

Figure 3. Impacts of an ethanol subsidy on fuel market in the presence of income tax

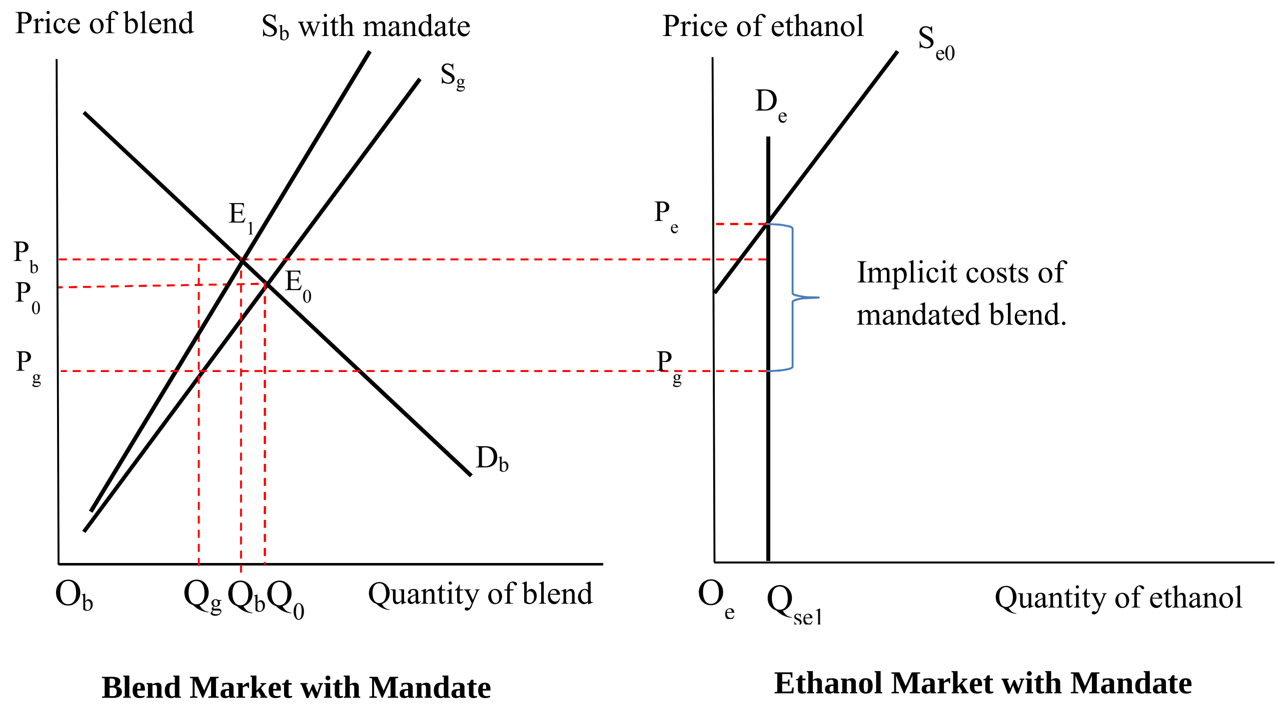

Figure 4. Impacts of an ethanol mandate for fuel market with no explicit economic incentive

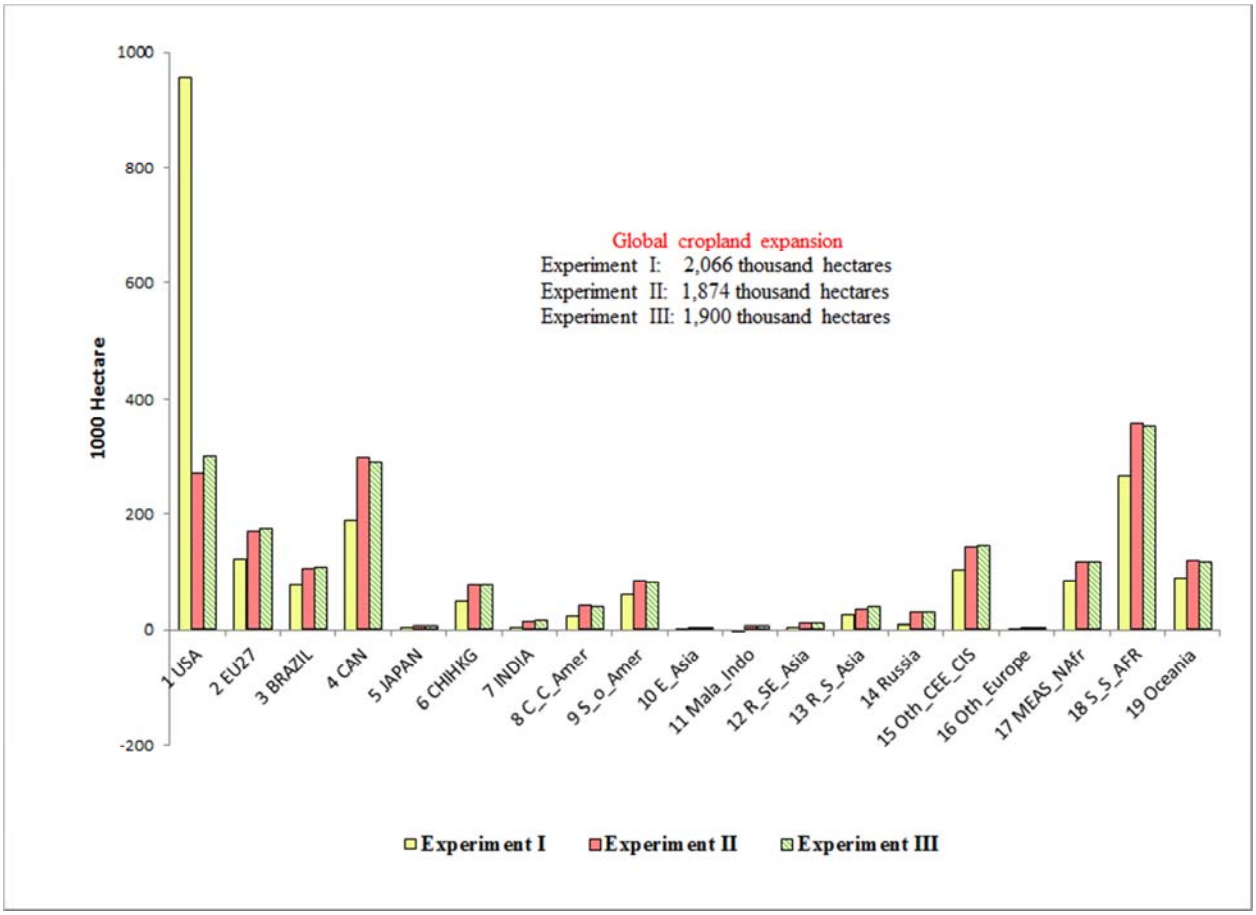

Figure 5. Expansion in cropland due to expansion in US ethanol production

Table 1. Price impacts of ethanol mandate under alternative experiments (Figures are percentage changes due to ethanol shock)

Commodity	Experiment I	Experiment II	Experiment III
Paddy Rice	2.4	7.2	6.9
Wheat	1.9	1.6	1.4
Coarse Grains	7.2	16.9	16.8
Oilseeds	2.5	2.6	2.6
Sugar Crops	3.5	0.9	0.9
Other Crops	2.5	3.0	3.0
Crude Oil	-2.9	-2.5	-1.2
Gasoline	6.2	4.3	-1.6

Table 2. Impacts of ethanol mandate on gasoline consumption
(Figures are in billion gallon gasoline equivalent except otherwise noted)

Experiments	Increase in US Ethanol Supply	Reduction in US gasoline consumption	Reduction in global gasoline consumption	US rebound effect*	Global rebound effect*
Experiment I	7.77	-12.44	-9.36	-1.60	-1.21
Experiment II	7.77	-11.49	-8.62	-1.48	-1.11
Experiment III	7.77	-8.06	-5.92	-1.04	-0.76

*Rebound effect is defined as: Reduction in gasoline / Increase in ethanol

Table 3. Impacts of ethanol mandate on trade balance by region
(Figures are in millions of 2004 dollars)

Region	Experiment I	Experiment II	Experiment III
USA	1,323	-1,034	-5,018
EU27	-413	505	2,343
BRAZIL	18	67	130
CAN	10	56	141
JAPAN	-101	309	1,054
CHIHKG	222	369	498
INDIA	-65	-12	105
C_C_Amer	228	403	411
S_o_Amer	-157	-80	42
E_Asia	-12	24	78
Mala_Indo	1	30	46
R_SE_Asia	-40	23	111
R_S_Asia	-7	8	44
Russia	-329	-301	-245
Oth_CEE_CIS	-46	4	120
Oth_Europe	-30	6	55
MEAS_NAfr	-640	-515	-223
S_S_AFR	26	74	148
Oceania	14	62	160

Table 3. Welfare impacts of US ethanol mandate by region (Figures are in millions of 2004 dollars)

Region	Experiment I	Experiment II	Experiment III
USA	-16,822	-15,339	-14,795
EU27	1,952	1,312	132
BRAZIL	173	194	151
CAN	-624	-588	-316
JAPAN	318	-168	-528
CHIHKG	134	67	-44
INDIA	503	448	262
C_C_Amer	-1,597	-1,616	-833
S_o_Amer	-643	-557	-279
E_Asia	411	175	-63
Mala_Indo	-66	-53	-9
R_SE_Asia	221	215	145
R_S_Asia	63	51	25
Russia	-940	-917	-724
Oth_CEE_CIS	42	26	-3
Oth_Europe	-443	-427	-330
MEAS_NAfr	-3,611	-3,503	-2,501
S_S_AFR	-897	-808	-474
Oceania	92	123	134
World	-21,734	-21,365	-20,050

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