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Biofuels Policies and Welfare: Is the Stick of Mandates Better than the Carrot of Subsidies?

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Harvey Lapan

and

GianCarlo Moschini

Abstract

Significant government support for biofuels has led to rapid growth in U.S. ethanol production and research to develop more advanced biofuels. In this paper we construct a general equilibrium, open economy model that captures the rationale typically invoked to justify government intervention in this setting: to alleviate the environmental impact of energy consumption and to decrease U.S. energy dependence on foreign sources. The model is used to study both the positive and normative implications of alternative policy instruments, including the subsidies and mandates specified by the 2007 Energy Independence and Security Act. From a positive perspective, we find that biofuels mandates are equivalent to a combination of fuel taxes and biofuels subsidies that are revenue neutral. From a welfare perspective, we show that biofuels mandates dominate biofuels subsidies, and that combining fuel taxes (rather than subsidies) with mandates would be welfare enhancing.

Key Words: Biofuels policies, Greenhouse gas emissions, Mandates, Second best, Subsidies, Welfare.

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1. Introduction

U.S. fuel ethanol production has skyrocketed in recent years, going from 1.65 billion gallons in 2000 to 9 billion gallons in 2008 (RFA 2009). The United States are now the largest world producer of ethanol, with one third more output than Brazil (an early large developer and user of ethanol as transportation fuel) and twelve times as much output as the next largest region (the European Union). It is apparent that this dramatic expansion of ethanol production owes much to critical support policies implemented by the United States. Specifically, US ethanol production currently benefits from a $0.45/gallon subsidy and a $0.54 duty on ethanol imports.[1] In addition, the Energy Policy Act of 2005 established a renewable fuel standard that mandated specific targets for renewal fuel use. Such quantitative "mandates" have been expanded considerably by the Energy Independence and Security Act (EISA) of 2007 which established that the annual use of renewable fuel should reach 36 billion gallons by 2022. The larger proportion of this target is to be accounted for by advanced biofuels (mostly cellulosic ethanol) the technological feasibility of which is still being debated. As of now, U.S. biofuels production is virtually all made up of corn-based ethanol, the production of which is mandated by EISA to increase to 15 billion gallons by 2015 (Yacobucci, 2008).

U.S. biofuels policies are rationalized in terms of the pursuit of a number of objectives. First, there is a continuing and deepening interest in developing alternative, greener and more secure energy sources. Environmental motivations are rooted in the worldwide concern about global climate change, and the role played by greenhouse gas (GHG) emissions that are produced with most energy consumption. The dependence of the United States on foreign oil is also relevant for both economic and political reasons. The petroleum share of US energy consumption is 40 percent, whereas domestic oil only contributes 15 percent to national energy production. Indeed, because this country accounts for nearly 25 percent of world petroleum consumption (Council of Economic Advisers, 2008), its choices are bound to have an appreciable effect on energy prices. Following last year's rise in fossil fuel prices, it is clear that the level and fluctuations in such prices can have a sizeable impact on US welfare. Compounding that, national security considerations arise when a large proportion of a basic commodity that is indispensable for US economic and military security, such as oil, comes from a volatile part of the world.

[1] The subsidy, which amounted to $0.51/gallon up to January 2009, is technically an excise tax credit available to operators that blend ethanol with gasoline. The import duty represents a secondary tariff, which adds to the normal 2.5 percent ad valorem tariff, and it is meant to prevent foreign ethanol production from being supported by the U.S. excise tax credit.

The hope is that bio-renewable fuels might alleviate the environmental impact of energy consumption and decrease the dependence of the United States on foreign energy sources. Furthermore, increasing biofuels production has the added implication of increasing the demand for agricultural production and thus is consistent with a long-standing commitment to support the farm sector in the United States and other developed countries.

Whereas the pursuit of such ambitious objectives clearly provides scope for government intervention in this area, existing policies are controversial. The massive use of corn for ethanol production (more than one third of the US corn output is estimated to be used in ethanol production in the 2008-09 crop year) is putting considerable demand pressure on land, contributing to rising prices for grains and other products. This development has the potential to bring considerable benefits to agricultural producers, especially in the Midwest. But rising food prices have led to widespread concerns about the economic impacts of biofuels policies in the wider context, in particular reigniting the earlier "fuel versus food" debate (Ford Runge and Senauer, 2007). Much work has been devoted to study some of the economic impacts of biofuels, including an emphasis on projecting the short term and long term impacts on prices, production decisions and trade flows using multimarket models (Elobeid and Tokgoz, 2008) or computable general equilibrium models (Hertel, Tyner and Birur 2008). These and other studies (Rajagopal and Zilberman, 2007, provide an interpretative review) have made considerable strides in documenting some current and expected market impacts of the ongoing biofuels development.

One of the motivations for promoting biofuels is the hope that they might provide a cleaner source of transportation fuel. On an energy equivalent basis, ethanol typically produces lower GHG emissions relative to gasoline, although this attribute is sensitive to the energy used to fire ethanol refineries (Wang, Wu and Huo, 2007). A necessary condition for a net positive environmental impact is that biofuels production, viewed from the perspective of life cycle analysis, yields more energy than the fossil energy used in its production, a fact that has been disputed by some for corn ethanol, but which seems now generally accepted (Shapouri, Duffield and Wang, 2002; Farrell et al., 2008). But concerns have recently focused on "indirect land use" effects: the notion that diverting corn to ethanol production in the United States might bring new marginal land into production elsewhere because of the increased overall demand for agricultural output (Searchinger *et al.* 2008). The computed indirect land use effects of planned biofuels mandates could be quite sizeable (Hertel, Tyner and Birur, 2008).

Insofar as the documented and potential market impacts of biofuels production are traceable to the policies that are promoting their development, an interesting set of questions concerns the welfare evaluation of these policies. For the case of the US ethanol subsidy, de Gorter and Just (2009a) have provided an initial concrete effort in this direction by analyzing how this tax credit interacts with existing price-contingent production subsidies. They emphasize the "rectangular" deadweight cost of subsidizing ethanol production in a setting where no such production activity would otherwise take place, and provide some numerical illustration that net welfare changes (defined as the sum of Marshallian surpluses measured in a partial equilibrium setting) are negative and large. de Gorter and Just (2009b) extend the inquiry by specifically looking at the effects of the ethanol mandate, as envisioned by the renewable fuel standard established by EISA, and provide some interesting analysis of the interaction of the ethanol mandate and subsidy.[2]

What appears lacking in existing work is a perspective that casts welfare analysis in a normative context that explicitly accounts for the market failures that are held to play a critical role in this setting. As discussed earlier, one of the arguments in favor of biofuels is the hope that they might alleviate the environmental impact of energy consumption. The presumed market failure assumption should be explicitly built into the policy environment for the purpose of policy assessment. Holland, Hughes and Knittel (2009) do that by framing the problem as that of choosing a low carbon fuel standard, and provide some interesting analytical and numerical results. What they do not address explicitly is the national "energy security" argument that ascribes benefits to reducing US oil imports, *ceteris paribus*. In this paper we complement and generalize the analysis of existing studies by building a model that closely represents the structural elements of the U.S. ethanol industry and models the explicit policy tools that play a critical role in U.S. biofuels production. We address the international implications of the problem, including the U.S. dependence of oil imports, by casting the analysis in an open economy setting, and we provide both a positive and a normative evaluation of the main policy tools (taxes, subsidies and mandates).

Specifically, in this paper we build a (simplified) general equilibrium structure of two trading countries, United States and rest-of-the-world (ROW), in which the agricultural and energy sectors are explicitly linked. The model is rooted in a competitive structure with upward sloping supply of corn, and where corn production can be used for food and feed, for ethanol production and for export. An explicit technology describes the conversion of corn to ethanol, and equilibrium entails free entry of new

[2] For example, the introduction of a tax credit (a production subsidy) in a setting where the mandate is binding leads to a decrease in the price of fuel (blend of gasoline and ethanol) and thus acts as a consumption subsidy (an outcome that is presumably at odds with the stated policy objective of reducing GHG emissions).

ethanol plants into the industry. Ethanol is blended with gasoline to satisfy domestic demand for transportation fuel arising from a representative household. The model distinguishes domestic and foreign components and explicitly captures the term-of-trade effects arising both in the oil market and in the grain market. Whereas such term-of-trade effects have the traditional interpretation of trade models, it is apparent that, for oil imports, they are also a vehicle for a coherent representation of the (security) benefits of reducing oil imports. The model also captures the consumption externalities (e.g., GHG emission from energy consumption) that affect household utility and thus impact welfare, and allows for a differential pollution effect for ethanol and unblended gasoline.

The model structure permits the derivation of a number of interesting results. From a positive perspective, we characterize the market equilibrium effects of the policy tools that are used in the ethanol market, thereby complementing and extending the analysis of de Gorter and Just (2009b). A particularly useful result that we derive in this setting is to show that an ethanol quantity mandate is equivalent to a combination of an ethanol production subsidy and a fuel (gasoline) tax that are revenue neutral. The normative welfare analysis centers on characterizing "optimal" biofuels policies in the context of the specific second-best framework being studied. Again, we compare and contrast the alternative uses of ethanol subsidy and ethanol mandates, along with a fuel tax, and derive the optimal form of these policy instruments. A very interesting result that we derive concerns the comparison of a subsidy-only policy (a price instrument) and a mandate-only policy (a quantity instrument). We show that the (optimal) ethanol mandate yields higher welfare than the (optimal) ethanol subsidy. For reasons clarified in the derivation of this result, the equivalence between a price instrument and a quantity instrument that one typically expects in competitive models without uncertainty does not attain in our case.

2. The Model

We construct a simplified general equilibrium structure that replicates the positive analysis of some existing studies, but that allows us to perform welfare analysis in a second-best setting. The presence of an externality, the emission of greenhouse gases due to fuel consumption, together with the assumption that the country's policies affect world prices of corn and oil provide the reasons why domestic government policy has the potential to increase domestic welfare. However, restricting the set of policy instruments – ultimately to just biofuels policies – implies that the first-best outcome cannot be reached. The structure of our model allows us to perform second-best comparisons among these policy instruments.

2.1. Production

We assume there is a fixed endowment of a numeraire good, which can be consumed or used in production. There are two primary goods, corn and domestic oil, produced using the numeraire good and fixed resources (such as land, oil reserves, etc), and production of each exhibits increasing marginal cost. The total (private) cost of producing the aggregate domestic corn quantity X_c is given by $C(X_c)$, from which the inverse supply function for corn is $p_c^s = C'(X_c)$, and the private cost of producing the aggregate oil output S_o is $\Omega(S_o)$, implying the inverse supply function $p_o^s = \Omega'(S_o)$, where (p_c^s, p_o^s) denote "supply" prices (received by domestic producers). Oil is also supplied by foreign producers. The primary product corn can be consumed or can be, via a fixed-proportion technology described shortly, converted into ethanol, while the primary product oil can be converted, again via a fixed proportions technology, into gasoline. The final product, fuel (energy) can be obtained through various blends of ethanol and gasoline.

Given the assumption of a Leontief technology, the (long-run) production function for ethanol is written as $x_e^v = \min\{ax_c, \tilde{z}_e\}$, where ethanol x_e^v is here measured in volume units (gallons), x_c is the amount of corn used in ethanol production, a is a production coefficient, and $\tilde{z}_e$ is an index of all other inputs used per unit of ethanol production.[3] By current estimates, one bushel of corn produces approximately 2.75 gallons of ethanol (Eidman, 2007), that is, $a \cong 2.75$. But conversion of corn to ethanol also produces valuable byproducts, such as dried distiller's grains with solubles (DDGS), which is a close substitute for corn as feed (Mathews and McConnell, 2009). To simplify, we assume that DDGS and corn are perfect substitutes in feed use. If a unit of corn produces δ_1 units of byproduct, the price of which is proportional to that of corn, say $\delta_2 p_c$, then that is equivalent to assuming that the production of ethanol requires fewer (net) units of corn, that is $x_e^v = \min\{\rho x_c, \tilde{z}_e\}$, where $\rho = a/(1-\delta_1\delta_2)$. Furthermore, we need to recognize that ethanol has a lower energy content than gasoline, so that the quantity of total "fuel" (gasoline and ethanol-blended gasoline) is written as

[3] The long-run interpretation of interest in this paper presumes free entry of new ethanol plants. The industry has indeed experienced a furious growth in this dimension, with the number of operating plants increasing from 54 in January 2000 to 170 in January 2009 (RFA 2009).

$x_f \equiv x_g + \gamma x_e^v$, where $\gamma \cong 0.7$.[4] Thus, it is convenient to change the units of measurement, so that ethanol is measured in gasoline energy-equivalent units. To that end, define $x_e \equiv \gamma x_e^v$ and $z_e \equiv \gamma \tilde{z}_e$. In these units, and accounting for the value of byproducts, ethanol production is written as

(1) $$x_e = \min\{\alpha x_c, z_e\}$$

where $\alpha \equiv \gamma a/(1-\delta_1\delta_2)$ and z_e is an index of all other inputs used in ethanol production, when the latter is measured in energy-equivalent units. With that, the (constant returns to scale) cost function for ethanol production is $(p_c/\alpha + w_e)x_e$, where w_e denotes the price of all inputs other than corn (inclusive of the rental price of capacity).[5] Thus, at given prices, the long-run supply price of ethanol is:

(2) $$p_e^s = \frac{p_c}{\alpha} + w_e$$

Refining of oil into gasoline is assumed to also take place according to a fixed proportion technology, and so the production of unblended gasoline from oil is:

(3) $$x_g = \min\{\beta x_o, z_g\}$$

where x_o is the total quantity of oil refined, β is the number of gallons of refined gasoline per barrel of crude oil and z_g denotes the aggregate of other inputs used in gasoline production. Hence, the (constant returns to scale) cost function for gasoline production is $(p_o/\beta + w_g)x_g$, where w_g is the price of z_g (inputs other than oil, including the rental price of capacity). Thus, the supply price of gasoline is:

[4] A gallon of pure ethanol contains 76,000 BTUs (British Thermal Units) of energy, whereas a gallon of gasoline contains 110,000 BTUs of energy (NREL 2008).

[5] In essence, we assume the price of these other inputs is constant in terms of the numeraire good. This could happen if the other inputs were produced under constant returns using only the numeraire, or if there were fixed endowments of these other inputs and they were perfect substitutes, in utility, for the numeraire.

(4) $$p_g^s = \frac{p_o}{\beta} + w_g$$

2.2. Demand

We assume a domestic population of consumers who have quasi-linear preferences. The consumers' utility depends upon three private goods: fuel (blend of gasoline and ethanol), corn, and a composite good that aggregates all other goods. The consumers' utility is also negatively affected by the pollution associated with the (aggregate) consumption of energy. Such preferences can be exactly aggregated up to a single representative agent's preference ordering. Furthermore, the quasilinear structure allows for an internally consistent welfare analysis (that is, independently of the distribution of income/endowments). The representative consumer's utility is therefore written as

(5) $$U = y + \phi\left(D_f\right) + \theta\left(D_c\right) - \sigma\left(x_g + \lambda x_e\right)$$

where y represents the consumption of the composite commodity (the numeraire),[6] and the vector (D_f, D_c) represents the consumption of fuel and corn. The standard assumption of quasiconcavity of the utility function in the choice variables, given the quasilinear structure, translates into the condition that $\phi(\cdot)$ and $\theta(\cdot)$ are concave functions. The last term in the utility function, through the function $\sigma(\cdot)$, represents the environmental damages that come from aggregate fuel utilization. Note that the parameter λ permits the relative pollution efficiency of ethanol and gasoline to differ, where the two are measured in comparable energy units, so $\lambda < 1$ if and only if ethanol is less polluting than gasoline per energy unit.

The US consumer demand for fuel (including gasoline blended with ethanol, with everything measured in gasoline energy equivalent units) is derived from maximizing the utility function in (5), taking as given the external effects of the function $\sigma(\cdot)$, so that the inverse demand function is $p_f = \phi'(D_f)$ and the demand function is $D_f(p_f) = (\phi')^{-1}(p_f)$.

---

[6] As noted in footnote 1, these many other goods in the utility function can be aggregated to a single index, denoted by y, provided all these other goods are perfect substitutes in consumption for the numeraire, or that their opportunity cost of production is constant in terms of the numeraire good.

The domestic consumer demand for corn as food or feed is similarly obtained maximizing the utility function in (5), so that the inverse demand function is $p_c = \theta'(D_c)$. Inverting this relation yields the domestic demand curve for direct corn consumption $D_c(p_c) = (\theta')^{-1}(p_c)$.

2.3. Foreign sector

We assume there are three traded goods: corn, oil and the numeraire good. In the model, ethanol trade is precluded. The possibility of exporting U.S. ethanol is not interesting because it is widely believed that the U.S. corn-based technology is not as efficient as the Brazilian sugar-cane-based production. Neglecting imports of ethanol is justified by the existence of the $0.54/gallon import duty, which is effectively acting as a prohibitive tariff.[7] As for the traded commodities, the model assumes that, under free trade, the United States imports oil and exports corn.[8] Because in the welfare analysis of this paper we are only concerned with domestic welfare, we do not need to be explicit about the cost structure and preferences of the ROW. Assuming that their economic policy is given, we only need to model the relevant behavioral functions (the ROW's export supply of oil and import demand for corn). Here, and throughout the paper, we follow the convention by which the overstruck bar denotes foreign variables. The ROW's import demand for corn is written as $\bar{D}_c(\bar{p}_c)$, where $\bar{p}_c$ is the net price in the foreign market, and $\bar{D}'_c < 0$. Similarly, we let $\bar{S}_o(\bar{p}_o)$ denote the ROW's export supply of oil to the United States, where $\bar{S}'_o > 0$.[9]

3. Competitive Equilibrium

Because we assume world oil and corn prices are endogenous, and because there is an externality due to pollution, in the model we are developing there are three sources for government intervention to

[7] A limited amount of ethanol is imported (about 0.6 billion gallons in 2008), mostly from countries that are part of the Caribbean Basin Initiative and thus enjoy a limited exemption from the secondary ethanol import tariff.

[8] It may either import or export the numeraire good. Recall that, in the model, the world prices of corn and oil are the relative prices in terms of this numeraire good.

[9] In general, these behavioral equations could depend upon both relative prices, i.e., the ROW import demand for corn might also depend upon the price of oil. To justify this specification, which simplifies the analysis but is not critical, we assume the production and preference structure is the same in the ROW as in the United States. Naturally, the ROW's import demand for corn is the demand for U.S. corn exports.

increase domestic welfare. The endogenous export price for corn means that the United States can gain by restricting corn exports, which is the standard terms of trade (or monopoly power) argument for trade restrictions. Similarly, the United States could gain from restricting oil imports for two possible reasons: (i) the standard terms of trade arguments, whereby restrictions on oil imports lower world oil prices, and (ii) U.S. national security may be undermined by oil imports, even if world prices are exogenous. Finally, the government has an incentive to intervene due to the market failure of pollution. Hence:

Remark 1. Maximizing domestic welfare in this setting requires three policies: an export tax on corn; an import tax on oil; and a tax on pollution emissions.

If these three policies were implemented, then there would be no welfare-increasing rationale for other policies, such as ethanol subsidies or mandates. However, if some of these policies are not politically feasible, then the country – from the perspective of domestic welfare – is in a second-best situation and it is possible that policies which indirectly address these inefficiencies, such as ethanol mandates or subsidies, might improve domestic welfare even though these indirect policies will not be able to achieve the optimum solution.

Because we wish to focus on ethanol policies in this paper, we initially assume that there are no other domestic taxes or subsidies in place. Furthermore, we know that international commitments through the WTO constrain border policies (as well as some domestic policies), at least in principle.[10] Thus, we assume:

Assumption 1. No border policies, such as import taxes on oil, or export taxes on corn, are feasible. Also, there are no domestic corn or oil taxes or subsidies.

This assumption implies world prices equal domestic producer prices, and that domestic prices to buyers and sellers, in the corn and oil markets, are the same. Hence, this assumption implies $p_o^s = p_o = \overline{p}_o$ and $p_c^s = p_c = \overline{p}_c$, a condition that we will maintain throughout the analysis.

[10] A domestic consumption tax on oil, coupled with a production subsidy for domestic oil producers, would be equivalent to an import tariff on oil. Hence, constraining border policies means an implicit constraint on domestic policy.

3.1. Corn and ethanol markets

From the assumed cost structure of the agricultural sector, the market supply function of corn can be written as: $X_c = (C')^{-1}(p_c) \equiv S_c(p_c)$. There are three uses for domestic corn output: domestic consumption (by households),[11] with demand $D_c(p_c)$, exports, with demand $\bar{D}_c(\bar{p}_c)$, and ethanol production. For any given amount of x_c devoted to ethanol production, equilibrium in the corn market must satisfy

$$(6) \qquad S_c(p_c) = D_c(p_c) + \bar{D}_c(p_c) + x_c$$

which means that the residual supply of corn to the ethanol sector is:

$$(7) \qquad Q(p_c) \equiv S_c(p_c) - D_c(p_c) - \bar{D}_c(p_c)$$

Clearly, $Q'(p_c) > 0$. Also, using (2), we get the inverse ethanol supply curve:

$$(8) \qquad p_e^s(x_e) = \frac{p_c(x_e/\alpha)}{\alpha} + w_e$$

where $p_c(\cdot) \equiv Q^{-1}(\cdot)$. Thus the derived inverse ethanol supply curve is upward sloping, $dp_e^s/dx_e = \left[\alpha^2 Q'(p_c)\right]^{-1} > 0$.

3.2. Oil and gasoline markets

The domestic supply function for oil is obtained by inverting the aggregate marginal production cost, yielding $S_o(p_o) \equiv (\Omega')^{-1}(p_o)$, and the foreign supply of oil to the United States is written as $\bar{S}_o(p_o)$, where again we assume no tariffs or quotas on imported oil are feasible. The per unit production cost of unblended gasoline, which is the selling price of gasoline to refiners assuming perfect competition, can be written as:

[11] Obviously corn is not consumed directly by households but it is used as an input for food production. Assuming competition throughout, we can treat corn as a final consumption good without loss of generality.

(9) $$\left(\frac{p_o}{\beta}+w_g\right)=p_g \quad \Leftrightarrow \quad p_o=\left(p_g-w_g\right)\beta$$

Because gasoline production is directly proportional to total domestic use of oil, we can write unblended gasoline supply as a function of oil price, and therefore as a function of gasoline price:

(10) $$x_g=\beta\left(\bar{S}_o(p_o)+S_o(p_o)\right)\equiv\psi\left(p_g-w_g\right)$$

Thus, the derived supply of unblended gasoline to the US market is upward sloping:

(11) $$\frac{dx_g}{dp_g}=\psi'=\beta^2\left[\bar{S}_o'(p_o)+S_o'(p_o)\right]>0$$

4. Comparative Statics of Equilibrium

Before analyzing the welfare implications of various policies, let us first consider the equilibrium conditions and the comparative statics of these polices. We start by considering the effects of a fuel tax and ethanol subsidy.[12]

4.1. Equilibrium with fuel taxes and ethanol subsidies

For the purpose of characterizing market equilibrium we assume that ethanol, adjusted for energy content, is a perfect substitute for gasoline over the relevant range. Hence, equilibrium in the fuel market requires $D_f(p_f)=x_g+x_e$. Alternatively, the relevant equilibrium conditions can be represented in terms of arbitrage conditions, using inverse demand and supply functions, that account for the policy instruments of interest. For the latter, we wish to explicitly model the unit (blending) subsidy for ethanol, which we denote as b. Furthermore, it is important to consider the possibility of a fuel tax, a standard instrument typically invoked to address market failures in this setting (Parry and Small, 2005).

[12] Of the three policy instruments that might be considered here (ethanol subsidy, gasoline tax, and fuel tax), one is redundant. Specifically, a fuel tax of t and an ethanol subsidy of b is fully equivalent to a gasoline tax of t and an ethanol subsidy of $(b-t)$.

Hence, let t denote the unit tax on fuel (gasoline and/or blend of gasoline and ethanol). Then the arbitrage relations implied by equilibrium in the energy market are:

$$
\begin{aligned}
p_g^s\left(x_g\right) &= p_f\left(x_g + x_e\right) - t \\
p_e^s\left(x_e\right) &= p_f\left(x_g + x_e\right) - t + b
\end{aligned}
\tag{12}
$$

where $p_f(\cdot)$ is the inverse demand for fuel $x_f \equiv x_g + x_e$, $p_e^s(\cdot)$ is the inverse supply of ethanol, and $p_g^s(\cdot)$ is the inverse supply of gasoline. Using $\partial p_f / \partial x_f = 1/D_f'$, $\partial p_g / \partial x_g = 1/\psi'$, and $\partial p_e / \partial x_e = 1/(\alpha^2 Q')$, the comparative static relations between tax, subsidy and quantities is given by:

$$
\begin{bmatrix} dt \\ -db \end{bmatrix} = \frac{-1}{r_1 r_2 r_3 N} \begin{bmatrix} \left(r_1 + r_3\right) r_2 & r_2 r_3 \\ -r_1 r_2 & r_1 r_3 \end{bmatrix} \begin{bmatrix} dx_g \\ dx_e \end{bmatrix}
\tag{13}
$$

where $N \equiv \left(-D_f' + \alpha^2 Q' + \psi'\right) > 0$ and the terms $r_i \in \left(0,1\right)$ satisfy

$$
r_1 \equiv \frac{-D_f'}{N}, \quad r_2 = \frac{\alpha^2 Q'}{N}, \quad r_3 \equiv \frac{\psi'}{N}, \quad \sum_{i=1}^{3} r_i = 1
\tag{14}
$$

Inverting yields:

$$
\begin{bmatrix} dx_g \\ dx_e \end{bmatrix} = \left(-N\right) \begin{bmatrix} r_1 r_3 & -r_2 r_3 \\ r_1 r_2 & \left(r_1 + r_3\right) r_2 \end{bmatrix} \begin{bmatrix} dt \\ -db \end{bmatrix}
\tag{15}
$$

The impact of the fuel tax or the ethanol subsidy on the prices and quantities of gasoline, ethanol and fuel, as derived in equations (13) and (15), are summarized in Table 1. As expected, an ethanol subsidy raises ethanol production and price, decreases gasoline consumption and price, raises total fuel consumption and has an ambiguous impact on pollution, even if $\lambda < 1$. A fuel tax decreases ethanol and gasoline consumption, and thus lowers total fuel consumption and pollution, regardless of the value of λ. Thus, both policies are potentially beneficial due to their impact on corn export prices and oil import prices, as well as their potential impact on pollution.

4.2. Equilibrium with mandates

A central element of the U.S. biofuels policy, expanded by EISA, concerns the use of quantitative "mandates" on the amount of biofuels production. Such mandates could be implemented in several different ways—as a mandated level of consumption or as a mandated proportion of total consumption. De Gorter and Just (2009b) and Holland, Hughes and Knittel (2009) consider policies that require a given proportion of fuel to be accounted for by the alternative fuel. Whereas it is true that the implementation of the ethanol mandate by the Environmental Protection Agency relies on mandating a blending standard for obligated parties, enforced through a system of renewable identification numbers, it is also true that the chosen standard is selected to meet the specific overall quantitative target set by EISA (given an expected total consumption level). In this paper, therefore, we model mandates as specifying a minimum level of consumption. Obviously, in a competitive deterministic setting the mandates will have no effect if they do not bind.

4.2.1. Quantity mandates with ethanol subsidy

Because a binding mandate means that blenders, who sell fuel, must use more ethanol than would otherwise be profitable, one cannot use an arbitrage condition for relating ethanol, gasoline and fuel prices. Rather, the equilibrating condition that we use in this model is a zero profit condition for the fuel industry. Letting x_e^M represent the exogenous ethanol mandate, and b the ethanol subsidy (if any), the zero profit condition is:

$$(16) \qquad p_f\left(x_g + x_e^M\right)\cdot\left(x_g + x_e^M\right) - p_g\left(x_g\right)\cdot x_g - \left(p_e\left(x_e^M\right) - b\right)\cdot x_e^M = 0$$

where x_e^M is exogenous and $p_e(x_e^M) - b \geq p_f(x_g + x_e^M) \geq p_g(x_g)$ (with strict inequality if the mandate binds). With a binding mandate, the price of ethanol is strictly determined by the mandate. Given that fuel prices are demand-determined and ethanol prices are supply-determined, then (16) determines $x_g(x_e^M, b)$. Finally, (16) also shows that in equilibrium the fuel price must be a weighted average of the price of gasoline and ethanol.

As is well known, unambiguous comparative statics results in a setting such as ours ultimately rely on stability conditions. The equilibrium condition in the energy market can be written in terms of the excess demand function as:

$$J\left(p_g\right) \equiv D_f\left(p_f\right) - x_g\left(p_g\right) - x_e^M = 0 \tag{17}$$

Hence, Walrasian stability requires $dJ/dp_g = D_f' \cdot (dp_f/dp_g) - \psi' < 0$. Assuming that demand and supply curves have their conventional slopes $(\psi' > 0 > D_f')$, and using (16), the stability condition can be rewritten as:

$$\frac{dJ}{dp_g} = \left(\frac{-\psi' D_f'}{x_f}\right)\left[MR_f - MC_g\right] < 0 \tag{18}$$

where MR_f denotes the marginal revenue associated with an increase in fuel sales, i.e., $MR_f \equiv p_f + x_f \cdot (dp_f/dx_f)$, and MC_g denotes the increase in expenditures on gasoline due to an increase in gasoline sales, i.e., $MC_g \equiv p_g + x_g \cdot (dp_g/dx_g)$. Define MC_e as the increase in expenditures on ethanol due to an increase in ethanol sales, i.e., $MC_e \equiv p_e + x_e \cdot (dp_e/dx_e)$. Differentiating (16) yields:

$$\left(MR_f - MC_g\right)dx_g = \left(MC_e - MR_f - b\right)dx_e^M - x_e^M db \tag{19}$$

Using the foregoing definitions and (14), the marginal effects in (19) satisfy $MR_f = p_f - x_f/(r_1 N)$, $MC_g = p_g + x_g/(r_3 N)$ and $MC_e = p_e + x_e^M/(r_2 N)$. Equation (19) can then be re-written as:

$$\left[\left(p_f - p_g\right) - \frac{x_g + x_e^M}{r_1 N} - \frac{x_g}{r_3 N}\right]dx_g = \left[\frac{x_g + x_e^M}{r_1 N} + \frac{x_e^M}{r_2 N} + \left(p_e - b - p_f\right)\right]dx_e^M - x_e^M db \tag{20}$$

The condition for (Walrasian) stability of the fuel market in (18), in the presence of the ethanol mandate, requires the expression in brackets on the left-hand-side of (20) to be negative. When the mandate is binding and $dx_e^M = 0$, then from (20) it is immediate, as discussed in DeGorter and Just (2009b), to conclude that:

Lemma 1. Given a binding quantity ethanol mandate, an ethanol subsidy sufficiently small so that the mandate still binds leads to increased gasoline, and fuel, usage, higher oil prices and lower fuel prices, but does not affect ethanol prices.

4.2.2. Quantity mandates: A re-interpretation

Next, consider the relationship between only mandates (with $b = 0$) and the simultaneous use of a fuel tax and ethanol subsidy such that net tax revenue is constant (and equal to zero). From $tx_f = bx_e$ it follows that:

(21) $$x_f dt = \left(bdx_e - tdx_f\right) + x_e db$$

Using (21) in conjunction with (13) yields:

(22) $$Hdx_g = -Kdx_e$$

where

(23) $$H \equiv \left\{\frac{x_g + x_e}{r_1} + \frac{x_g}{r_3} - tN\right\} > 0$$
$$K \equiv \left\{\frac{x_g + x_e}{r_1} + \frac{x_e}{r_2} + (b-t)N\right\} > 0$$

Note that $H > 0$ follows directly from the stability condition invoked earlier, whereas $K > 0$ holds because we must have $b \geq t$ for the mandate to bind. The case of a pure (binding) mandate is given by (20) with $b = 0$ and $db = 0$. Noting that, by definition, $(p_f - p_g) = t$ and $(p_e - p_f) = (b - t)$, then it is apparent that (22) is equivalent to (20). We conclude with the following result, which will prove quite useful for the welfare analysis that follows.

PROPOSITION 1. An ethanol mandate is equivalent to a combination of an ethanol blending subsidy and a fuel tax that are revenue neutral.

Using (13) and (22), the changes in the subsidy and tax required to support the increased ethanol mandate (subject to the balanced budget constraint) are:

$$
\begin{aligned}
&\frac{dt}{dx_e^M} = \frac{x_e + r_2\left(r_1 + r_3\right)N\left(b-t\right) + r_2 r_3 t N}{r_1 r_2 r_3 N H} \\
(24)\qquad &\frac{db}{dx_e^M} = \frac{x_f + r_1 r_2\left(b-t\right)N - r_1 r_3 t N}{r_1 r_2 r_3 N H}
\end{aligned}
$$

Around the laissez faire equilibrium $(t=b=0)$, increasing the mandate is equivalent to raising both the ethanol subsidy and fuel tax, in a revenue neutral fashion. Further, note that around the laissez-faire equilibrium, $db/dx_e^M > dt/dx_e^M$, implying that the *net* subsidy to ethanol $(b-t)$ also increases. However, for sufficiently large mandates, further increases in the mandate may correspond to reduced ethanol subsidies and, even more plausibly, reduced net ethanol subsidies. Nevertheless, an increased mandate must yield a higher ethanol price for suppliers. Although we normally expect that increasing the mandate raises the blended fuel prices, and thus reduces total consumption, it turns out that the comparative statics effect on total fuel consumption (and fuel price) is actually indeterminate:

$$
(25)\qquad \frac{d\left(x_g + x_e^M\right)}{dx_e^M} = \left(\frac{H-K}{H}\right) = \frac{\left(x_g/r_3\right) - \left(x_e^M/r_2\right) - bN}{H}
$$

Evaluating (25) at the point where the mandate just binds $\left(t=b=0 \Rightarrow p_g = p_e = p_f\right)$, the numerator can be written as:

$$
(26)\qquad \left(x_g/r_3\right) - \left(x_e^M/r_2\right) = N p_g \left\{\frac{\varepsilon_e - \varepsilon_g}{\varepsilon_g \varepsilon_e}\right\}
$$

where: $\varepsilon_g \equiv (dx_g/dp_g)(p_g/x_g)$ and $\varepsilon_e \equiv (dx_e/dp_e)(p_e/x_e)$ are the elasticities of derived supply of gasoline and ethanol, respectively. Hence, it follows that, as noted by de Gorter and Just (2008):[13]

Lemma 2. If the supply of ethanol is more elastic than the supply of gasoline (oil), then over some domain an ethanol mandate raises total fuel consumption and lowers the price of fuel.

This latter result implies that, even without taking into account the impact of U.S. mandates on pollution generated in the rest of the world, the ethanol mandate could raise domestically generated pollution even if $\lambda < 1$.

5. Welfare Implications of Policy

The utility function in (5) gives welfare under quasi-linear preferences as a function of consumption of the numeraire, of corn and of fuel, taking into account the impact of the externality. Domestic consumption of the numeraire is endowment less resources used up in production, plus net exports, all measured in numeraire units. Hence:

$$\begin{aligned} W = &\left\{ I - C\left(D_c + \bar{D}_c + x_c\right) - \Omega\left(S_o\right) - w_e x_e - w_g x_g + \left[p_c \bar{D}_c - p_o \bar{S}_o\right]\right\} \\ &+ \phi\left(x_g + x_e\right) + \theta\left(D_c\right) - \sigma\left(x_g + \lambda x_e\right) \end{aligned} \tag{27}$$

In this equation, I is the aggregate endowment of the numeraire, $C(D_c + \bar{D}_c + x_c)$ is the cost of domestic corn production, $\Omega(S_o)$ is the cost of domestic oil production, $(w_e x_e)$ and $(w_g x_g)$ are the costs of other inputs used in ethanol and gasoline production, all measured in numeraire units. Finally, the term $[p_c \bar{D}_c - p_o \bar{S}_o]$ represents net exports, and hence represents imports of the numeraire (under balanced trade). Note that if there is no international trade, then prices do not directly affect domestic welfare – it is the impact prices have on resource allocation that affects welfare. With international

[13] The results in Lemma 2 differ somewhat from those articulated in de Gorter and Just (2009b) because the latter models mandates as a (percent) fuel standard. Whereas such comparative statics results are obviously sensitive to the way the mandate is modeled, it should be clear that the welfare effects discussed in the next section remain robust to that specification choice (because the welfare effects ultimately depend on the overall production of gasoline and ethanol supported by the policy).

trade, prices affect domestic welfare because price changes redistribute wealth between domestic and foreign agents.

We seek to characterize conditions under which welfare is maximized, i.e., $dW = 0$. Taking the total differential of (27) yields:

$$
\begin{aligned}
dW &= \phi' \cdot \left(dx_g + dx_e\right) + \theta' \cdot dD_c - C' \cdot \left(dD_c + d\bar{D}_c + dx_c\right) - \Omega' \cdot dS_o \\
&\quad - w_e dx_e - w_g dx_g + p_c d\bar{D}_c + \bar{D}_c dp_c - p_o d\bar{S}_o - \bar{S}_o dp_o - \sigma' \cdot \left(dx_g + \lambda dx_e\right)
\end{aligned} \tag{28}
$$

Under Assumption 1 (no direct intervention in the corn or oil markets and no border tariffs), the marginal production cost for domestic corn and the marginal utility of domestic corn consumption are both equal to the price of corn, that is $\theta' = p_c = C'$, and the marginal cost of domestic oil production equals its price, that is $\Omega' = p_o$. Also, the marginal utility of domestic fuel consumption is equal to the retail price of fuel, that is $\phi'(x_g + x_e) = p_f$. Using these conditions, grouping terms, and using the fact that the assumed production structure implies $dx_g = \beta \cdot \left(dS_o + d\bar{S}_o\right)$ and $dx_e = \alpha \cdot dx_c$, we obtain:

$$
dW = \left\{p_f - \frac{p_o}{\beta} - w_g - \sigma'\right\} dx_g + \left\{p_f - w_e - \frac{p_c}{\alpha} - \lambda\sigma'\right\} dx_e + \bar{D}_c dp_c - \bar{S}_o dp_o \tag{29}
$$

From the zero profit condition for refining and ethanol production (rents are transferred to the corn market), the prices received by the sellers of gasoline and the sellers of ethanol are:

$$
\begin{aligned}
p_g^s &= \frac{p_o}{\beta} + w_g \\
p_e^s &= \frac{p_c}{\alpha} + w_e
\end{aligned} \tag{30}
$$

So that (29) becomes:

$$
dW = \left\{p_f - p_g^s - \sigma'\right\} dx_g + \left\{p_f - p_e^s - \lambda\sigma'\right\} dx_e + \bar{D}_c dp_c - \bar{S}_o dp_o \tag{31}
$$

Note that with no externalities $(\sigma' = 0)$ and no taxes/subsidies (i.e., $p_f = p_g^s = p_e^s$), the only welfare effects are the terms-of-trade effects. Define the "effective" tax on fuel and "effective" subsidy to ethanol by:[14]

$$\begin{aligned} &t \equiv p_f - p_g^s \\ &b \equiv p_e^s - (p_f - t) \end{aligned} \tag{32}$$

so that (31) can be rewritten as

$$dW = \{t - \sigma'\}dx_g - \{b - t + \lambda\sigma'\}dx_e + \bar{D}_c dp_c - \bar{S}_o dp_o \tag{33}$$

Recall that, with no domestic or border policies in the corn or oil market, corn prices are in 1-1 correspondence with ethanol output and oil supplies are in 1-1 correspondence with the price of oil. Hence, we can write ethanol supply as a function of corn prices as $x_e = \alpha Q(p_c)$, where $Q(p_c)$ is the supply of corn to the ethanol industry in equation (7). From this we obtain $dx_e = \alpha Q' dp_c$, implying

$$dp_c = \frac{dx_e}{\alpha Q'} \tag{34}$$

Similarly, gasoline production is directly proportional to total domestic use of oil, so that we can write unblended gasoline supply as a function of oil price, and therefore as a function of gasoline price, as in equation (10). From (10) we obtain $dx_g = \psi' dp_g$, and from $p_o = (p_g - w_g)\beta$ we get $dp_o = \beta dp_g$. So

$$dp_o = \frac{\beta dx_g}{\psi'} \tag{35}$$

Substitute (34) and (35) into (33) to obtain:

[14] Given the tax is on fuel, the net subsidy to ethanol is, of course, $(b - t)$.

(36) $$dW = \left\{ t - \sigma' - \frac{\beta \bar{S}_o}{\psi'} \right\} dx_g - \left\{ b - t + \lambda\sigma' - \frac{\bar{D}_c}{\alpha Q'} \right\} dx_e$$

For future reference, define:

(37) $$W_g \equiv \frac{\partial W}{\partial x_g} = p_f\left(x_g + x_e\right) - p_g\left(x_g\right) - \sigma'\left(x_g + \lambda x_e\right) - \frac{\beta \bar{S}_o\left(p_o\left(x_g\right)\right)}{\psi'\left(p_g\left(x_g\right)\right)}$$

(38) $$W_e \equiv \frac{\partial W}{\partial x_e} = p_f\left(x_g + x_e\right) - p_e\left(x_e\right) - \lambda\sigma'\left(x_g + \lambda x_e\right) + \frac{\bar{D}_c\left(p_c\left(x_e\right)\right)}{\alpha Q'\left(p_c\left(x_e\right)\right)}$$

Consider the second (partial) derivatives in the variables x_g and x_e:

(39) $$\begin{aligned} W_{gg} &= \frac{1}{D_f'} - \frac{1}{\psi'} - \sigma'' - \left\{ \frac{(\psi')^2\left(\bar{S}'/\left(S' + \bar{S}'\right)\right) - \left(\bar{S}/\left(S + \bar{S}\right)\right)\psi''\psi}{(\psi')^3} \right\} \\ W_{ee} &= \frac{1}{D_f'} - \frac{1}{\alpha^2 Q'} - \lambda^2\sigma'' + \left\{ \frac{\bar{D}_c' Q' - \bar{D}_c Q''}{\alpha^2 (Q')^3} \right\} \\ W_{eg} &= W_{ge} = \frac{1}{D_f'} - \lambda\sigma'' \end{aligned}$$

Assumption 2. The function $W(x_g, x_e)$ is concave in its arguments and the variables x_g and x_e are substitutes, *i.e.*, $W_{eg} < 0$.

The functional conditions that must obtain for $W_{ee} < 0$, $W_{eg} < 0$ are standard curvature conditions, but the condition for W_{gg} is more complicated because it depends on the relationship between the domestic and foreign oil supply curve. Still, the assumption on W_{gg} is not unreasonable.[15]

[15] For example, suppose that $S\left(p_o\right) = \kappa\bar{S}\left(p_o\right)$ for some positive scalar κ. Then sufficient conditions for Assumption 2 to hold are: $\sigma'' \geq 0$, $Q'' \geq 0$ and $\psi(\cdot)$ is logconcave.

We are interested in drawing the contours $W_g = 0$ and $W_e = 0$ in (x_g, x_e) space. The concavity and substitute conditions from Assumption 2 guarantee that $dx_g/dx_e\big|_{W_e=0} = -W_{ee}/W_{eg} < 0$ and $dx_g/dx_e\big|_{W_g=0} = -W_{eg}/W_{gg} < 0$. These conditions, in conjunction with the determinant condition for concavity, imply that the contour for $W_e = 0$ has a steeper slope dx_g/dx_e than that for $W_g = 0$, yielding the shapes illustrated in Figure 1.

The optimal solution in Figure 1 is still a second best solution, as discussed earlier. To achieve this (second best) optimum, we need two (independent) policy instruments – ethanol subsidies and fuel taxes (or equivalently, as noted earlier, ethanol subsidies and unblended gasoline taxes). An alternative mix that would (may) allow the solution to be achieved would be binding ethanol mandates and fuel taxes.

We discuss first the case when the policy instruments are ethanol subsidies and taxes on fuel. From (13) and (15) choosing (x_g, x_e) is equivalent to choosing (t, b). Because $dW = 0$ at this second-best solution, then from (36) these policies are characterized as follows.

Proposition 2. Assuming the only feasible policies are domestic subsidies to ethanol producers and a tax on all fuel consumption, the optimal policy is given by:

(40) $$t^* = \sigma' + \frac{\beta \bar{S}_o}{\psi'} > 0 \text{ and } b^* = \frac{\bar{D}_c}{\alpha Q'} + (1-\lambda)\sigma' + \frac{\beta \bar{S}_o}{\psi'}.$$

Note that both t^* and b^* will be positive, provided $\lambda \leq 1$. As discussed earlier, the reasons for intervention are the externality and the impact of domestic policy on our import/export prices.[16] In the case of the fuel tax, the reasons reinforce each other, and hence the tax is unambiguously positive; the same is true for the *gross* subsidy to ethanol b^*. In this setting, of course, interest should center on the *net* subsidy to ethanol, defined as $\hat{b} \equiv b^* - t^*$. It turns out that this can be of either sign.

Lemma 3. If the tax t applies only to gasoline, so that the ethanol subsidy represents a net subsidy, the optimal policy is:

[16] Similar results for the fuel tax would hold if the world price of fuel were exogenous but, for political economy reasons, domestic welfare was a decreasing function of oil imports.

$$t^* = \sigma' + \frac{\beta \bar{S}_o}{\psi'} > 0 \quad \text{and} \quad \hat{b} = \frac{\bar{D}_c}{\alpha Q'} - \lambda\sigma' .$$

Thus, the net subsidy to ethanol is potentially ambiguous – increasing the net ethanol subsidy is beneficial, due to the terms of trade effect in the corn market, but detrimental due to the pollution effect $(\lambda > 0)$. For a closed economy setting, as in de Goerter and Just (2009b) and Holland, Hughes and Knittel (2009), only the carbon externality motive remains, and in such a case one would obtain $t^* = \sigma'$ and $\hat{b} = -\lambda\sigma'$, implying that both gasoline and ethanol ought to be taxed.

Returning to the use of fuel taxes and ethanol subsidies, the optimal policy in the presence of terms-of-trade effects is usually expressed in elasticity terms. Doing so yields:

$$(41) \qquad t^* = \sigma' + m_o \frac{p_g}{\varepsilon_g}$$

$$(42) \qquad b^* = \frac{(p_e - w_e)(\bar{D}_c/Q)}{\varepsilon_c} + m_o \frac{p_g}{\varepsilon_g} + (1-\lambda)\sigma'$$

$$(43) \qquad b^* - t^* = \frac{(p_e - w_e)(\bar{D}_c/Q)}{\varepsilon_c} - \lambda\sigma'$$

where: $m_o \equiv \bar{S}_o / (S_o + \bar{S}_o)$ is the import share of domestic oil consumption, ε_g is the elasticity of the derived supply of unblended gasoline (from oil), defined earlier, and $\varepsilon_c \equiv (dQ/dp_c)(p_c/Q)$ is the elasticity of the residual supply of corn to the ethanol industry (hence this elasticity is larger than any of the demand or supply elasticities individually).

Lemma 4. The optimal tax on ethanol is increasing in the share of oil imported, and decreasing in the elasticity of aggregate oil supply. The optimal (net) subsidy to ethanol is increasing in the ratio of corn exports to corn use in ethanol, and decreasing in the elasticity of the residual supply curve.

Note that if only one policy instrument (such as an ethanol subsidy or ethanol mandate) is used, then in general the second best optimum pictured in Figure 1 cannot be reached.[17] We now turn to a welfare comparison of these two instruments.

5.1. Welfare when ethanol subsidies are the only policy instrument

As shown earlier, ethanol subsidies affect both gasoline using and ethanol usage. Substituting (15) in to (36) yields:

$$(44) \qquad dW = N\left[-W_g\left(r_1 r_3 dt + r_2 r_3 db\right) + W_e\left(\left(r_1 + r_3\right) r_2 db - r_1 r_2 dt\right)\right]$$

Assuming only ethanol subsidies are used (or the tax rate is exogenously given) then $dt = 0$ and:

$$(45) \qquad \frac{\partial W}{\partial b} = N\left\{W_e\left(r_1 + r_3\right) r_2 - W_g r_2 r_3\right\} \quad = N\left(r_1 + r_3\right) r_2 \left\{W_e + \eta W_g\right\}$$

where $\eta \in (0, -1)$ is the slope, dx_g / dx_e, in gasoline-ethanol space, of the one dimensional locus generated by changing the subsidy while holding the tax rate constant, that is:

$$(46) \qquad \eta \equiv \frac{\left(\partial x_g / \partial b\right)}{\left(\partial x_e / \partial b\right)} = \left(\frac{-r_3}{r_1 + r_3}\right) = \left(\frac{-\psi'}{\psi' - D_f'}\right).$$

Equation (45) shows the subsidy affects welfare through its impact on both ethanol and gasoline use. If we have only one policy instrument, we are restricted – in terms of Figure 1 – to move along a one-dimensional subset of the two-dimensional space, and the term η represents the slope of this feasible locus (see dotted line in Figure 1, where x^0 represents the *laissez faire* point).

The optimal ethanol subsidy must solve $\partial W / \partial b = 0$ and thus, from (45), $W_e + \eta W_g = 0$. Using prior definitions, with an exogenous tax t this requires:

---

[17] A singular exception would be if gasoline taxes could be used and the optimal net ethanol subsidy were zero. Clearly, this is a zero probability event. Note that, if fuel taxes are the only policy instrument, then this second best solution can never be supported.

(47) $$\left(\frac{\bar{D}_c}{\alpha Q'} - \lambda\sigma' + p_f\left(x_e + x_g\right) - p_e\left(x_e\right)\right) + \left(\frac{-\psi'}{\psi' - D'_f}\right)\left(p_f\left(x_e + x_g\right) - p_g\left(x_g\right) - \sigma' - \frac{\beta\bar{S}_o}{\psi'}\right) = 0$$

The solution to the constrained welfare optimum, denoted $\left(\tilde{x}_e(t), \tilde{x}_g(t)\right)$, is found using equation (47) and the arbitrage equation:

(48) $$p_f\left(x_e + x_g\right) - p_g\left(x_g\right) - t = 0$$

Note that, for $t = 0$, $W_g < 0$; since $\eta < 0$, the solution must therefore occur somewhere in the domain where $W_g < 0$ and $W_e < 0$. That is, the subsidy is such that ethanol is "overproduced" $\left(W_e < 0\right)$, given the availability of gasoline, because the ethanol subsidy indirectly reduces the use of gasoline. In fact, it is apparent that this property is true for all $t > 0$ such that $t < \sigma' + \beta\bar{S}_o/\psi'$.[18] Finally, the optimal subsidy is given, definitionally, by $\tilde{b}(t) = p_e\left(\tilde{x}_e\right) - p_f\left(\tilde{x}_g + \tilde{x}_e\right) + t$. Given the above, the welfare effects when the ethanol subsidy is the only policy instrument can be summarized as follows:

PROPOSITION 3. Suppose the only policy instrument is an ethanol subsidy/tax (i.e., $t = 0$). Then the optimal subsidy is given by:

$$b^* = \frac{\bar{D}_c}{\alpha Q'} - \lambda\sigma' + \left(\frac{\psi'}{\psi' - D'_f}\right)\left(\sigma' + \frac{\beta\bar{S}_o}{\psi'}\right).$$

In addition:

(i) at the optimal subsidy, welfare is decreasing in both ethanol and gasoline consumption;

(ii) the constrained optimal subsidy may be positive even if, when both ethanol subsidies and fuel taxes are allowed, the net subsidy to ethanol is negative;

(iii) Even if there are no corn exports, a sufficient condition to guarantee that (positive) ethanol subsidies are welfare improving is $\lambda \le \psi'/(\psi' - D'_f)$. Provided $\lambda < 1$, this condition is more likely to hold if the demand for fuel is not very price responsive.

---

[18] This expression is, of course, endogenous unless $\sigma'' = 0$ and $\bar{S}_o/\psi' = 0$, where the latter occurs if there are no oil imports or if world oil price is exogenous.

In practice, of course, taxing fuel consumption takes place. In the United States the federal gasoline tax of $ 0.184/gallon, however, has not been changed since 1993. How such a tax rate ought to be adjusted in response to an optimal biofuels subsidy policy is the object of the following result.

PROPOSITION 4. Let the tax on fuel be exogenously determined, and let $b^*(t)$ denote the optimal ethanol subsidy. Then: $\forall\, t < \sigma' + \beta\bar{S}_o / \psi'$, an increase in the fuel tax raises welfare.

The proof of Proposition 4 is reported in Appendix A2.

5.2. Welfare when mandates are the only policy instrument

We turn now to the welfare implications of mandates. From (36), and recalling (32), when the mandate is the only active policy instrument we have:

$$\text{(49)} \qquad \frac{dW}{dx_e^M} = \left\{ \left(p_f - p_g\right) - \sigma' - \frac{\beta\bar{S}_o}{\psi'} \right\} \frac{\partial x_g}{\partial x_e^M} + \left\{ \left(p_f - p_e\right) - \lambda\sigma' + \frac{\bar{D}_c}{\alpha Q'} \right\}$$

From (20), and recalling the definitions of the terms r_i in (14), the impact of a binding ethanol mandate on gasoline sales is:

$$\text{(50)} \qquad \frac{dx_g}{dx_e^M} = -\left[\frac{\psi' + s\psi'\left(\dfrac{-D_f'}{\alpha^2 Q'}\right) + (1-s)\left(p_e - p_g\right)\left(\dfrac{-D_f'\psi'}{x_f}\right)}{\psi' + \left(-D_f'\right)(1-s) - s\left(p_e - p_g\right)\left(\dfrac{-D_f'\psi'}{x_f}\right)} \right]$$

where $s \equiv (x_e^M / x_f) \in (0,1)$ denotes the share of ethanol in fuel consumption. Note that here the price of fuel is a weighted average of the gasoline and ethanol prices, $p_f = sp_e + (1-s)p_g$, implying $(p_e - p_f) = (1-s)(p_e - p_g)$ and $(p_f - p_g) = s(p_e - p_g)$.

The "form" of the FOC for the optimal choice of the mandate is exactly the same as for the subsidy – the difference is in the term $(\partial x_g / \partial x_e)$, that is, in terms of the responsiveness of gasoline usage to the (induced) change in ethanol usage. In either case, since there is only one policy variable, one is forced to move in a one dimensional subset of the two dimensional welfare space (x_g, x_e). As can be seen from comparing (46) and (50), when evaluated at the same point (x_g, x_e),

$$\left.\frac{\partial x_g}{\partial x_e}\right|_{mandate} < \left.\frac{\partial x_g}{\partial x_e}\right|_{subsidy} < 0$$

It follows that if the mandate and subsidy are set to yield the same ethanol output, the mandate will yield lower gasoline use (lower p_g) and hence lower aggregate fuel consumption (higher p_f).

Turning to the first order conditions, we have:

PROPOSITION 5. If the only feasible policy is an ethanol mandate, then a binding mandate will increase welfare if: $\left.\frac{dW}{dx_e^M}\right|_{p_f=p_e} = \left(\frac{\bar{D}_c}{\alpha Q'}\right) - \lambda\sigma' + \left(\sigma' + \frac{\beta\bar{S}_o}{\psi'}\right)\left(\frac{\psi' + s\psi'\left(-D_f'/\alpha^2 Q'\right)}{\psi' + (1-s)\left(-D_f'\right)}\right) > 0$.

The proof of this proposition follows from (49), using (50), and evaluating at the laissez-faire point $p_f = p_g = p_e$.[19]

The non-equivalence of an ethanol subsidy and an ethanol mandate is further illustrated by the following result, which highlights the fact that subsidies and mandates are different policy instruments due to their differing impact on gasoline consumption.

Lemma 5. If, when only ethanol subsidies can be used, it would be optimal to tax ethanol (i.e, $b^* < 0$), it may still be optimal to have a binding mandate when mandates are the only feasible policy.

[19] Both here, and for the subsidy, we assume some ethanol would be produced in the *laissez-faire* equilibrium. If not, a negative term reflecting the difference between the *laissez-faire* fuel price and the supply price of the first unit of ethanol would be added to the first expression inside the bracket: i.e., it would be $\left((\bar{D}_c/\alpha Q') - \lambda\sigma' - v\right)$, where $v \equiv p_e(x_e = 0) - p_f$ represents what de Gorter and Just (2008) refer to as "water" in the mandate or subsidy.

This lemma follows from comparing the results of Proposition 3 and Proposition 5. Specifically, the expression in Proposition 5 coincides with that for b^* in Proposition 3 when $s=0$. Thus, if it is optimal to tax ethanol ($b^*<0$) and $s=0$, then a positive mandate would not increase welfare. But, the expression in Proposition 5 is monotonically increasing in s. Furthermore, at $s=1$ the expression in Proposition 5 must be positive, provided $\lambda \le 1$. Thus, provided some ethanol is used in the *laissez-faire equilibrium*, there are always parameter values such that $b^*<0$ and yet a positive ethanol mandate increases welfare.

5.3. Comparing ethanol subsidies and ethanol mandates

It is apparent that, in our setting, it would be better to be able to use two instruments, rather than only one of them. It is also of considerable interest to directly compare ethanol mandates and ethanol subsidies, but because of the second (or third) best nature of the problem, this is not easily done. The strategy that we use to derive a welfare ranking of the two instruments exploits the insight derived earlier in Proposition 1, that is, an ethanol mandate is equivalent to a combination of ethanol subsidy and fuel tax that is revenue-neutral. Hence, return to the case in which both fuel taxes and ethanol subsidies can be used. Tax revenue at the optimal solution is defined as $T^* = t^* x_f - b^* x_e = t^* x_g - (b^* - t^*) x_e$. Using the results of Proposition 2, collecting terms and converting to elasticities yields:

$$(51) \qquad T^* = \sigma' \cdot \left(x_g + \lambda x_e \right) + \left\{ \frac{p_o \bar{S}_o}{\varepsilon_g} - \frac{p_c \bar{D}_c}{\varepsilon_c} \right\}$$

where, as earlier, ε_g is the elasticity of gasoline supply and ε_c is the elasticity of the residual supply curve of corn to the ethanol industry. This expression is very likely to be positive for a variety of reasons. Even if there were no externalities (i.e., $\sigma'=0$), the value of oil imports $p_o \bar{S}_o$ exceeds the value of corn exports $p_c \bar{D}_c$, and the elasticity of the residual supply curve for corn is most likely larger than the elasticity of supply of gasoline. The presence of the externality (i.e., $\sigma'>0$), of course, only reinforces the likelihood that optimal net tax revenues are positive.

Assumption 3. Assuming both ethanol subsidies and fuel taxes can be used, net tax revenue at the optimal solution is positive.

Before comparing ethanol subsidies with ethanol mandates, it is useful to consider iso-tax revenue curves in gasoline-ethanol space. Consider output vectors (x_g, x_e), and the supporting taxes and subsidies $t(x_g, x_e)$ and $b(x_g, x_e)$. Let T denote the tax revenue associated with (x_g, x_e):

(52) $$T \equiv t\left(x_g, x_e\right)\left(x_g + x_e\right) - b\left(x_g, x_e\right)x_e$$

Totally differentiating (52), and using (13) and (23), implies:

(53) $$dT = -\frac{1}{N}\left(Hdx_g + Kdx_e\right)$$

Hence, the iso-tax revenue condition $dT = 0$ yields $dx_g / dx_e = -K/H < 0$ (recall that, under the assumed stability condition, $K > 0$ and $H > 0$). That is, the iso-tax revenue curves are negatively sloped in the (x_g, x_e) space. Furthermore, equation (53) makes it clear that iso-tax revenue curves corresponding to higher net tax revenue are closer to the origin – i.e., entail lower ethanol usage, given gasoline usage. To summarize the foregoing:

Lemma 6. Let $S\left(x_g, x_e, T_i\right) \equiv \left\{(x_g, x_e) \,\middle|\, t(x_g, x_e)x_f - b(x_g, x_e)x_e \le T_i\right\}$ denote the set of points that yield at most a given tax revenue T_i. If $T_1 > T_0$, then $S\left(x_g, x_e, T_0\right) \subset S\left(x_g, x_e, T_1\right)$.

Figure 2 illustrates these iso-tax revenue curves. The properties of these iso-tax revenue curves, in conjunction with Assumption 3, allow us to rank, according to the welfare criterion, ethanol mandates and ethanol subsidies. Specifically:

PROPOSITION 6. Let $T^* > 0$ denote the net tax revenue corresponding to the optimal policy when both fuel taxes and ethanol subsidies may be used. Then

(i) Ethanol mandates yield higher welfare than an ethanol subsidy policy.

(ii) If both fuel taxes and ethanol subsidies can be used, but there is an upper bound, T_0, on net revenue that is permitted to be raised by the policy combination, then, provided $T_0 < T^*$, increasing the upper bound raises welfare.

The proof of this proposition, detailed in Appendix A3, relies on comparing the maximized value of the welfare function, by choosing the instrument (b,t), under the constraint the policy yield (no more than) a given tax revenue, say $\hat{W}(T_0)$. In view of Lemma 6, constraining the tax revenue to be zero (as with the mandate) lowers welfare, relative to the second best optimum (which by assumption yields $T^* > 0$). But the tax revenue T_s of a subsidy-only policy is negative, and hence, as shown in Appendix A3, it follows that $\hat{W}(T_s) < \hat{W}(0) < \hat{W}(T^*)$. Furthermore, because the constrained optimum problem allows both taxes and subsidies, whereas the subsidy-only problem requires $t = 0$, it follows that $\hat{W}(T_s)\big|_{t=0} \leq \hat{W}(T_s)$. That is, the solution for the subsidy-only problem must be weakly inferior (and almost surely is strictly inferior) to the constrained optimum using both instruments, but having the same net tax revenue outlay.

6. Conclusion

The search for renewable and cleaner energy sources that reduce pollution and reliance on potentially unstable foreign sources of nonrenewable energy is a stated policy goal of many large countries worldwide, including the United States. Government intervention to reduce reliance on polluting, non-renewable energy sources will have significant economic consequences in the years to come and it is important that these consequences be well understood. While there are several possible sources of renewable energy, we have focused in this paper on biofuels (which for the United States essentially means corn-based ethanol), though in principle the same techniques could be used to study the impact of policies on other forms of renewable energy.

We reach several noteworthy and novel conclusions. First, we show that ethanol mandates are equivalent to a policy of taxing fuel and subsidizing ethanol (*i.e.,* providing tax credits to ethanol blenders). Thus the equivalence between price and quantity tools that holds when the quantity *restricts* the unfettered market outcome (i.e, an import restriction or a pollution restriction) does not hold here. The reason for the nonequivalence is because the mandates are imposed upon multi-product (or multi-input) firms and thus change the mix of products the firm produces (or uses). Illustrations of such mandates include the biofuels policy discussed in this paper, but also apply to other situations, such as mandates that require electric power firms to generate a certain fraction of their power from renewable sources, or the CAFE (Corporate Average Fuel Economy) regulations to improve vehicles' average fuel economy. Because the binding mandates (virtually by definition) raise firms' costs, zero-profit competitive equilibrium implies that part of the cost increases are shifted on to other products, and thus the mandate acts not just as a subsidy to the use of ethanol (the mandated product) but also as a tax on the other activity carried out by firms.

We also found that neither ethanol subsidies nor ethanol mandates alone can achieve multiple policy goals, and that in our framework coupling either policy with a fuel tax would be beneficial. This conclusion, in turn, allows us to derive a novel welfare ranking of the two instruments (biofuels subsidy or mandate) in isolation. Specifically, our analysis shows that an ethanol mandate is fully equivalent to a combination of fuel taxes and ethanol subsidies that revenue neutral. As discussed in the paper, it then follows that the use of a production/consumption mandate for ethanol actually leads to higher welfare than the use of ethanol subsidies.

There is broad scope for expanding the issues studied here. For one, the welfare interaction between the domestic economy and the rest of the world was captured just through world prices, but the model could readily be extended to recognize that domestic policy affects foreign greenhouse gas emissions. This "leakage" problem, as for example the case of indirect land use changes discussed in the introduction, clearly impacts domestic welfare. Moreover, there are significant dynamic issues that arise in this context and that we have not addressed explicitly in the model. Strategic considerations and international cooperation to address what is, ultimately, the global externality issue connected with climate change, are also outside the scope of the current paper. All that is the object of ongoing research projects of many researchers, and will no doubt define a good portion of the research agenda in this area for years to come.

Appendix A1. Notation summary

$x_o =$ quantity of oil

$x_g =$ quantity of unblended gasoline

$x_e^v =$ quantity of ethanol (in volume units)

$x_e =$ quantity of ethanol (in gasoline energy-equivalent units)

$x_f =$ quantity of total "fuel" (gasoline and ethanol-blended gasoline)

$x_c =$ quantity of corn used in ethanol production

$z_g =$ other variable inputs used in the production of gasoline

$z_e =$ other variable inputs used in the production of ethanol

$p_o =$ price of oil

$p_g =$ price of unblended gasoline

$p_e =$ price of (gasoline energy-equivalent) ethanol

$p_f =$ price of total fuel

$p_c =$ price of corn

$w_g =$ price of other inputs used in the production of gasoline

$w_e =$ price of other inputs used in the production of ethanol

$b^v =$ unit ethanol blending subsidy (at the moment $b^v \cong 0.51$ \$/gal.)

$b =$ unit ethanol blending subsidy when ethanol is measured in gasoline energy-equivalent units

$C(.) =$ aggregate cost function for domestic corn production

$\Omega(.) =$ aggregate cost function for domestic oil production

$D(.) =$ direct demand for fuel

$\overline{S}_o(.) =$ foreign supply of oil to the U.S. market

$S_o(.) =$ domestic supply of oil

$\psi(\cdot) =$ derived supply of unblended gasoline

$Q(\cdot) =$ derived supply of corn to the ethanol industry

$\varepsilon_g =$ elasticity of the derived supply of gasoline

$\varepsilon_c =$ elasticity of the (residual) supply of corn to the ethanol industry

$\varepsilon_e =$ elasticity of the derived supply of ethanol

Appendix A2. Proof of Proposition 4

Denote $V(b,t) \equiv W\left(x_g(b,t), x_e(b,t)\right)$ and let $b^*(t)$ be the optimal subsidy. From earlier, $b^*(t)$ is determined from:

$$V_b = W_e\left(\frac{\partial x_e}{\partial b}\right) + W_g\left(\frac{\partial x_g}{\partial b}\right) = \frac{\partial x_e}{\partial b}\left\{W_e + \eta W_g\right\} = 0;$$

where $\eta \in (0,-1)$ is as defined in (46). By the envelope theorem, $\frac{dV}{dt} = \frac{\partial V}{\partial t} + \frac{\partial V}{\partial b}\frac{\partial b^*}{\partial t} = \frac{\partial V}{\partial t}$, thus:

$$\frac{\partial V}{\partial t} = W_e\left(\frac{\partial x_e}{\partial t}\right) + W_g\left(\frac{\partial x_g}{\partial t}\right) = \frac{\partial x_g}{\partial t}\left\{\delta W_e + W_g\right\}$$

where $\delta \equiv \left(\frac{\partial x_e/\partial t}{\partial x_g/\partial t}\right) > 0 > \left(\frac{\partial x_g}{\partial t}\right)$. Note that η is the slope, dx_g/dx_e, in gasoline-ethanol space, of the one dimensional locus generated by changing the subsidy, holding the tax rate constant, while δ^{-1} is the slope, dx_g/dx_e, in gasoline-ethanol space, of the one dimensional locus generated by changing the tax rate, holding the subsidy rate constant. As discussed in the text, if the condition $t < (\sigma' + \beta\overline{S}_o^*/\psi')$ holds then $W_g < 0$. Because the FOC requires $W_e + \eta W_g = 0$, then $W_e < 0$ must hold as well. Recalling that $\partial x_g/\partial t < 0$ and $\delta > 0$, it follows that

$$\frac{dV}{dt} = \left(\frac{\partial x_g}{\partial t}\right)\left\{W_e\delta + W_g\right\} > 0 \ . \qquad \text{QED}$$

Appendix A3. Proof of Proposition 6

Consider the functions $x_g(b,t)$ and $x_e(b,t)$ as defined earlier, and assume the objective is to maximize welfare, subject to the constraint $\left[tx_f(t,b) - bx_e(t,b)\right] \le T_0$, using the instruments $\{b,t\}$:

$$\underset{b,t}{Max}\ W\left(x_g(b,t); x_e(b,t)\right) \quad s.t. \quad tx_f - bx_e \le T_0;$$

where T_0 is an exogenous scalar. The Lagrangean function for this problem is:

$$L = W\left(x_g(b,t); x_e(b,t)\right) + \tau\left(T_0 + bx_e - tx_f\right)$$

We do not restrict t or b to be non-negative. Since the constraint is an inequality constraint, $\tau \ge 0$. Optimizing yields these first order conditions:

$$L_b = \frac{\partial x_e}{\partial b}\left\{W_e + \eta W_g + \tau\left[b - t(1+\eta) + x_e \cdot \left(\frac{\partial x_e}{\partial b}\right)^{-1}\right]\right\} = 0$$

$$L_t = \frac{\partial x_g}{\partial t}\left\{W_e\delta + W_g + \tau\left[b\delta - t(1+\delta) - x_f \cdot \left(\frac{\partial x_g}{\partial t}\right)^{-1}\right]\right\} = 0$$

$$L_\tau = \left(T_0 + bx_e - tx_g\right) \geq 0; \quad \tau L_\tau = 0; \quad \tau \geq 0$$

where: $\eta \in (0,-1)$ and $\delta > 0$ were defined earlier. Call the solution to this constrained optimization problem $t^c(T_0), b^c(T_0), x_g^c(T_0), x_e^c(T_0), \tau^c(T_0)$, with optimized value $L\left(t^c(T_0), b^c(T_0), x_g^c(T_0), x_e^c(T_0), \tau^c(T_0)\right) = W\left(x_g^c(T_0), x_e^c(T_0)\right) \equiv \hat{W}(T_0)$.

Let $\left(b^*, t^*, x_g^*, x_e^*\right)$ refer to the (unconstrained) second-best solution described in Proposition 2, and $T^* = t^* x_f^* - b^* x_e^*$. If $T_0 \geq T^*$, the constraint on net tax revenue will not bind, so $\tau^* = 0$ and hence the second best solution $\left(b^*, t^*\right)$ applies. Call the welfare level for this case $W^* = \hat{W}\left(T^*\right) \quad \forall T \geq T^*$.

Next, suppose $T^* > 0$, and consider the constrained optimization problem for $T_0 < T^*$. Then, in this domain: $\hat{W}'(T_0) = \tau^*(T_0) > 0,$ since the constraint binds. As shown earlier, the ethanol mandate is equivalent to a {tax, subsidy} policy with a tax revenue constraint $T_0 = 0$; that is, $\left\{x_g^c(T_0), x_e^c(T_0)\right\}\Big|_{T_0=0} = \left\{x_g^m, x_e^m\right\}$ (i.e., the mandate solution). Welfare with the mandate is less than that which obtains when both taxes and subsidies can be independently used, provided $T^* \neq 0$.

Next, let $T_s \equiv -b^s x_e^s < 0$ denote net tax revenues (which are negative) under the constrained optimal ethanol subsidy when taxes are not feasible. Since $T_s < 0 < T^*$, it follows that constrained welfare, using both fuel taxes and subsidies, when net tax revenue is T_s must be less then that under a mandate; i.e., $\hat{W}(T_s) < \hat{W}(0) < \hat{W}\left(T^*\right)$. Finally, note that $W\left(t = 0, b^s\right) \leq \hat{W}(T_s)$, because the constrained optimum problem allows both taxes and subsidies, whereas the subsidy only problem requires $t = 0$. That is, the solution for the subsidy only problem is in the domain for the constrained revenue problem, and hence the subsidy only problem must be weakly inferior (and almost surely is strictly inferior) to the constrained optimum using both instruments, but having the same net tax revenue outlay. QED

References

Council of Economic Advisers, 2008. "Searching for Alternative Energy Solutions," Chapter 7 in the ***Economic Report of the President***, February.

de Gorter, H., and D.R. Just, 2008. The Law of Unintended Consequences: How the U.S. Biofuel Tax Credit with a Mandate Subsidizes Oil Consumption and Has No Impact on Ethanol Consumption, ***Working Paper*** WP 2007-20, Department of Applied Economics and Management, Cornell University (Updated October 2008).

de Gorter, H., and D.R. Just. 2009a. "The Welfare Economics of a Biofuel Tax Credit and the Interaction Effects with Price Contingent Farm Subsidies," ***American Journal of Agricultural Economics*** 91(2):477-488.

de Gorter, H., and D.R. Just. 2009b. "The Economics of a Blend Mandate for Biofuels." ***American Journal of Agricultural Economics*** 91 (in press)

Eidman, V.R., 2007. "Economic parameters for corn ethanol and biodiesel production," ***Journal of Agricultural and Applied Economics*** 39(2):345-56.

Elobeid, A., and S. Tokgoz. 2008. "Removal of U.S. Ethanol Domestic and Trade Distortions: Impact on U.S. and Brazilian Ethanol Markets," ***American Journal of Agricultural Economics*** 90: 918-932.

Farrell, A.E., R.J. Plevin, B.T. Turner, A.D. Jones, M. O'Hare, and D.M. Kammen. 2006. "Ethanol Can Contribute to Energy and Environmental Goals." ***Science*** 311(5760): 506–08.

Ford Runge, C., and Senauer, B., 2007. "How Biofuels Could Starve the Poor," ***Foreign Affairs***, May-June.

Hertel, T.W., W.E. Tyner and D.K. Birur, 2008. "Biofuels for all? Understanding the Global Impacts of Multinational Mandates," Department of Agricultural Economics, Purdue University, ***GTAP Working Paper*** No. 51.

Holland, S.P., J.E. Hughes, and C.R. Knittel, 2009. "Greenhouse Gas Reductions under Low Carbon Fuel Standards?," ***American Economic Journal – Economic Policy***, 1(1):106-146.

Mathews, K.H., Jr., and McConnell, M.J., 2009. ***Ethanol Co-Product Use in U.S. Cattle Feeding: Lessons Learned and Considerations***, ERS Report FDS-09D-01, USDA, April.

NREL (National Renewable Energy Laboratory), 2008. ***Ethanol Basics***, Clean Cities Fact Sheet, U.S. Department of Energy, October.

Parry, Ian W. H., and Kenneth A. Small, 2005. "Does Britain or the United States Have the Right Gasoline Tax?" ***American Economic Review***, 95(4): 1276–89.

Rajagopal, D., and Zilberman, D., 2007. "Review of Environmental, Economic and Policy Aspects of Biofuels, ***Policy Research Working Paper 4341***, The World Bank, September.

RFA (Renewable Fuel Association), 2009. ***Growing Innovation: 2009 Ethanol Industry Outlook***, February.

Searchinger, T.D., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T-H. Yu.*et al*. (2008) "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change." ***Science*** 319 (5867): 1238-1240.

Shapouri, H., J.A. Duffield and M. Wang, 2002. The Energy Balance of Corn Ethanol: An Update, USDA, ***Agricultural Economics Report*** No. 813, July.

Yacobucci, B.D., 2008. "Fuel Ethanol: Background and Public Policy Issues," ***CRS Report for Congress***, Congressional Research Service, Updated April 24.

Wang, M., M. Wu and H. Huo, 2007. "Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types," ***Environmental Research Letters*** 2:1-13.

Table 1: Comparative static effects of fuel taxes and ethanol subsidies

Impact of taxes and subsidies on price	Impact of taxes and subsidies on quantities
$\frac{\partial p_g}{\partial t} = \frac{\left(\partial x_g / \partial t\right)}{\psi'} = -r_1 < 0$	$\frac{\partial x_g}{\partial t} = -r_1 \psi' < 0$
$\frac{\partial p_f}{\partial t} = \frac{\left(\partial x_f / \partial t\right)}{D'} = \left(r_2 + r_3\right) > 0$	$\frac{\partial x_f}{\partial t} = \left(r_2 + r_3\right) D' < 0$
$\frac{\partial p_e}{\partial t} = \frac{\left(\partial x_e / \partial t\right)}{\alpha^2 Q'} = -r_1 < 0$	$\frac{\partial x_e}{\partial t} = -r_1 \alpha^2 Q' < 0$
$\frac{\partial p_g}{\partial b} = \frac{\left(\partial x_g / \partial b\right)}{\psi'} = -r_2 < 0$	$\frac{\partial x_g}{\partial b} = -r_2 \psi' < 0$
$\frac{\partial p_f}{\partial b} = \frac{\left(\partial x_f / \partial b\right)}{D'} = -r_2 < 0$	$\frac{\partial x_f}{\partial b} = -r_2 D' > 0$
$\frac{\partial p_e}{\partial b} = \frac{\left(\partial x_e / \partial b\right)}{\alpha^2 Q'} = \left(r_1 + r_3\right) > 0$	$\frac{\partial x_e}{\partial b} = \left(r_1 + r_3\right) \alpha^2 Q' > 0$

Figure 1. Welfare in ethanol-gasoline space

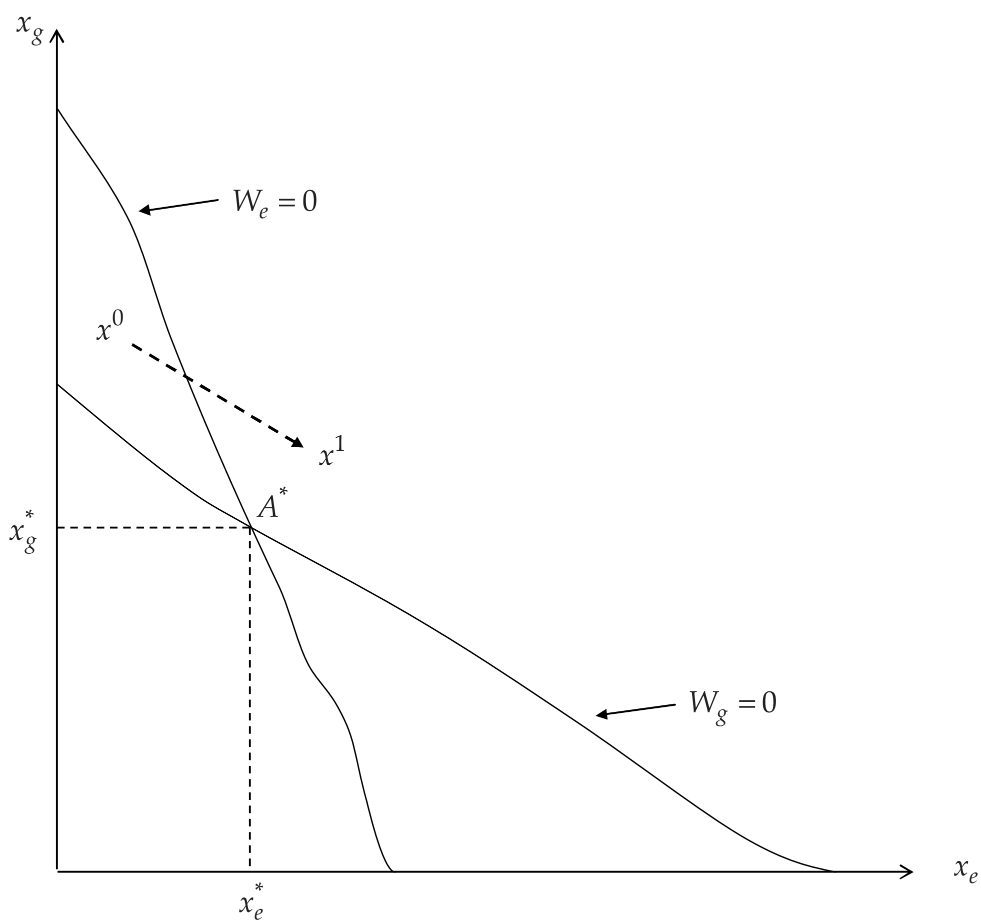

Figure 2. Iso-tax Revenue Curves