Journal of Environmental Economics and Management 63 (2012) 224–241

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Second-best biofuel policies and the welfare effects of quantity mandates and subsidies

Harvey Lapan, GianCarlo Moschini *

Department of Economics, Iowa State University, Ames, IA 50011, United States

ARTICLE INFO

Article history:
Received 11 November 2010
Available online 28 October 2011

Keywords:
Biofuel policies
Greenhouse gas emissions
Mandates
Second best
Subsidies
Welfare

ABSTRACT

The quest for biorenewable energy sources is held to justify a number of government interventions, including support policies for biofuels such as those responsible for the recent rapid growth of US ethanol production. This article provides an analytical assessment of such policies. 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 US 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 with mandates would be welfare enhancing.

1. Introduction

The recent dramatic expansion of the fuel ethanol industry is perhaps the most visible aspect of the quest for biorenewable sources of energy in the United States. US corn-based ethanol production has skyrocketed, going from 1.65 billion gallons in 2000 to 13.23 billion gallons in 2010 [22]. The United States are now the largest world producer of ethanol, with almost twice as much output as the next producer (Brazil, an early large developer and user of fuel ethanol). It is clear that this expansion of ethanol production owes much to the implementation of critical support policies. 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 (RFS) that mandated specific targets for renewable 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 (e.g., cellulosic ethanol) the technological feasibility of which is still being debated. As of now, US biofuel output is virtually all corn-based ethanol, the production of which is mandated by EISA to increase to 15 billion gallons by 2015 [27].

The purpose of this article is to provide a transparent and coherent framework for the welfare assessment of the key policy instruments that have led to the expansion of the US ethanol industry. To that end, the first step is to recognize that

* Corresponding author. Fax: +1 515 294 0221.
E-mail address: moschini@iastate.edu (G. Moschini).

[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 US excise tax credit.

0095-0696/$ - see front matter
doi:10.1016/j.jeem.2011.10.001

Nomenclature

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 $b^v \cong 0.45$ \$/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
$\bar{S}_o(.)$	foreign supply of oil to the US market
$S_o(.)$	domestic supply of oil
$\psi(\cdot)$	derived supply of unblended gasoline
$Q(\cdot)$	derived supply of corn to the ethanol industry
κ	RFS blending percentage
ε_g	elasticity of the derived supply of gasoline
ε_c	elasticity of the (residual) supply of corn to the ethanol industry

US biofuels policies are rationalized in terms of the pursuit of a number of objectives [7]. 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 hope is that biorenewable fuels might alleviate the environmental impact of energy consumption [21]. Separately, there is a desire to decrease the dependence of the United States on foreign energy sources. 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 [3], its choices are bound to have an appreciable effect on energy prices. The 2008 spike of fossil fuel prices are a recent reminder that the level and fluctuations in such prices can have a sizeable impact on US welfare. Finally, increasing biofuels production has the added implication of increasing the demand for agricultural production and thus is consistent with a long-standing US commitment to support its farm sector.

Whereas the pursuit of such ambitious objectives clearly provides scope for government intervention, existing policies are controversial. The massive use of corn for ethanol production (more than one-third of the US corn output is currently being used in ethanol production) is putting considerable demand pressure on land, contributing to rising prices for grains and other products. This brings considerable benefits to agricultural producers, especially in the Midwest. But rising food prices have led to widespread concerns about some unintended impacts of biofuels policies as exemplified by the "fuel versus food" debate [11]. The environmental implications are also being questioned. 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 [28]. 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 [26,10]. But concerns are being raised 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 [25,9]. The computed indirect land use effects of planned biofuels mandates could be quite sizeable [14].

Because the market and environmental impacts of biofuels are, to a large degree, traceable to the policies that are promoting their production, in this article we focus on the welfare evaluation of these policies. For the case of the US ethanol subsidy, de Gorter and Just [5] have provided a 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 [6] extend the inquiry by specifically looking at the effects of the ethanol mandate, as envisioned by the RFS established by EISA, and provide some interesting analysis of the interaction of the ethanol mandate and subsidy.[2]

[2] They show that 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

In this article we improve upon existing studies by casting welfare analysis in a normative context that explicitly accounts for the market failures that are held to play a critical role in this setting [13,16]. As noted, one of the arguments in favor of biofuels is the hope that they might alleviate the environmental impact of energy consumption. This presumed market failure assumption should be explicitly built into the policy environment for the purpose of policy assessment. Holland et al. [15] do that by framing the problem as that of choosing a low carbon fuel standard, and provide some interesting analytical and numerical results. Because of the closed-economy nature of their model, what they do not address explicitly are the trade implications of US biofuel policies, including the national "energy security" argument that ascribes benefits to reducing US oil imports. In this article, we improve on that framework and address the international implications of the problem by casting the analysis in an open economy setting and by endogenizing the price of oil. A distinct and separate question concerns the choice of policy instruments, an issue that has long been of interest in environmental economics [12]. In particular, a clear understanding of the economic impacts of biofuels subsidies and mandates is critical, in view of current US policy, and our analysis offer new and useful results in this regard.

Specifically, in this article we build a (simplified) general equilibrium structure of two trading regions, United States and rest-of-the-world (ROW), in which the agricultural and energy sectors are explicitly linked.[3] The model is rooted in a competitive equilibrium structure with upward sloping supply of corn (which can be used for food, feed, export, and for ethanol production) and free entry of new plants into the ethanol 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 terms-of-trade effects arising both in the oil market and in the grain market. Whereas such terms-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, a consideration often proffered to rationalize US biofuel support policies. The model also captures the environmental externalities (GHG emission from energy use) that affect household utility and thus impact welfare, and allows for a differential pollution effect for ethanol and unblended gasoline. We provide both a positive and a normative evaluation of the main policy tools (taxes, subsidies and mandates).

We derive 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. 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 mandate, 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, perhaps counter-intuitively, 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 also permits welfare analysis in a second-best setting. Two distinct considerations that provide scope for government policy to increase domestic welfare are explicitly represented in the model: the presence of an externality (the emission of greenhouse gases due to fuel consumption), and the assumption that the country's policies affect world prices of corn and oil (i.e., the United States is a "large country," meaning it can in principle exercise market power). As explained below, however, restrictions on the set of admissible policy instruments imply that the first-best outcome cannot be reached. The model that we build, therefore, is structured to permit second-best comparisons among policy instruments.

2.1. Production

In the model ethanol is produced from corn, which has the alternative uses of feed and/or food (domestically or in export markets), and ethanol is consumed as transportation fuel, in a blend with gasoline (which is obtained by refining oil, either domestically produced or imported). To get to the essence of the problem, therefore, we postulate the existence of only three final goods: corn, fuel, and everything else (the numeraire). Ethanol and gasoline are intermediate products, which when blended produce the final product fuel, and are produced from the two primary products corn and oil, respectively. Specifically, we assume a fixed endowment of a numeraire good, which can be consumed directly, used in production or exported (imported). Corn and domestic oil are produced using the numeraire good and fixed resources (e.g., land and oil reserves). Oil is also supplied by foreign producers. The primary product corn can be consumed directly,

(*footnote continued*)
reducing GHG emissions). With a numerical simulation model, Ando et al. [2] find that adding the ethanol tax credit to an ethanol mandate lowers social welfare (relative to a mandate without the tax credit).

[3] The bulk of the analysis presented in this article was developed in an earlier working paper [17].

exported, or converted into ethanol (via a fixed-proportion technology described shortly). The primary product oil (domestically produced or imported) is converted into gasoline. Transportation fuel (the final energy product available to consumers) is obtained by blending the intermediate products ethanol and gasoline.

The model we build is intended to have a long-run interpretation in a standard perfectly competitive setting,[4] and to capture the main stylized facts of the problem at hand. The main assumptions underlying the production side of the model are as follows. First, (aggregate) domestic production of corn and oil display increasing marginal costs. Hence, we postulate a convex total (private) cost of producing the domestic corn quantity X_c, denoted $C(X_c)$, and a convex private cost of producing the aggregate oil output S_o, denoted $\Omega(S_o)$, from which the inverse supply function for corn and oil are, respectively, $p_c^s = C'(X_c)$ and $p_o^s = \Omega'(S_o)$, where (p_c^s, p_o^s) denote "supply" prices (received by domestic producers).[5]

Next, we assume a Leontief technology (fixed proportions) for the transformation of corn and oil into ethanol and gasoline, respectively. Specifically, the production function for ethanol is written as $x_e^v = \min\{a x_c, \tilde{z}_e\}$, where ethanol x_e^v is 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. Similarly, the production of unblended gasoline from oil is: $x_g = \min\{\beta x_o, z_g\}$, 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.

Some discussion of these assumptions is in order at this juncture. First, that the United States, in aggregate, displays increasing marginal costs in the production of corn and oil is a reflection of existing natural resource constraints (e.g., land and oil reserves) that limit aggregate production. For example, increasing production of corn requires more arable land devoted to corn, which requires that land be bid away from alternative uses (other crops), which conceivably is only possible at increasing land rents (i.e., the standard competitive argument for an upward-sloping supply curve for an industry with either fixities or the increasing price of an input). Next, the Leontief technology assumption for the transformation of corn into ethanol is not only a convenient structural assumption, as discussed below, but also represents a very close representation of reality, as explained by many industry reports. For example, by current estimates one bushel of corn produces approximately 2.75 gal of ethanol [8], that is $a \cong 2.75$ in our notation. A similar argument applies to the refining of oil into gasoline. Finally, note that we are not assuming any additional fixity and/or capacity constraints for the ethanol industry. That is, consistent with our long-run interpretation of the model, we presume that there is free entry (or exit) of new ethanol plants. This assumption appears supported by the dynamics of the ethanol industry, which has experienced a furious growth in the number of plants in recent years.[6] Similarly, we assume no fixity and/or capacity constraints for the oil refining industry.

A re-parameterization of the ethanol production function is desirable to further increase its realism and also facilitate the analysis. First, conversion of corn to ethanol also produces valuable byproducts, such as dried distiller's grains with solubles (DDGS), which can substitute for corn as feed [18]. To capture this element in our model we assume δ_1 units of byproduct for each unit of corn used for ethanol. Furthermore, if we write the price of this byproduct as proportional to that of corn (i.e., $\delta_2 p_c$), a legitimate assumption because DDGS are a close substitute for corn as feed, then this 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 $\rho = a/(1-\delta_1\delta_2)$. Second, 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 $x_f \equiv x_g + \gamma x_e^v$, where $\gamma \cong 0.7$.[7] Thus, it is convenient to change the units of measurement, so that ethanol is measured in gasoline energy-equivalent units. To that end, we 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 $x_e = \min\{\alpha x_c, z_e\}$, 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.

Given the foregoing specification of the relevant production structure, 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).[8] Similarly, 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, at given prices, the long-run supply prices of ethanol and gasoline are, respectively:

$$p_e^s = \frac{p_c}{\alpha} + w_e \tag{1}$$

$$p_g^s = \frac{p_o}{\beta} + w_g \tag{2}$$

[4] The reformulation of some components of the model to represent an imperfect competition structure, to study the effects of possible market power, may provide opportunities for interesting extensions and future research. Needless to say, the competitive analysis of this article would be essential as a benchmark for any such extension.

[5] Throughout the article the s superscript on price symbols is used to denote supply prices (whenever there is a need to distinguish them from consumer-level prices).

[6] The number of operating ethanol plants increased from 54 in January 2000 to 204 in January 2011 [22].

[7] A gallon of pure ethanol contains 76,000 British Thermal Units (BTUs) of energy, whereas a gallon of gasoline contains 110,000 BTUs of energy [19].

[8] 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.

Because here ethanol and gasoline are expressed in units that have the same energy content, the total "fuel" that the production sector makes available to consumers is naturally defined as $x_f=(x_g+x_e)$. Thus, we are assuming that gasoline and ethanol are perfect substitutes in the production of fuel, and indeed (consistent with the realities of US gasoline retail practices) that they are available to consumers only as a blend. This perfect substitution assumption—conditional on having accounted for the different energy content of the two fuels—is natural: the presumption is that consumers ultimately care about the transportation value of fuel (e.g., "vehicle miles traveled," as in [16]), so that alternative fuels are valued on the basis of their energy content. Admittedly, by emphasizing its role as a so-called gasoline extender, this structure simplifies somewhat the current role of ethanol in the nation's fuel supply. Ethanol in fact also serves as an oxygenate additive/octane enhancer (to help gasoline burn cleaner), the demand for which has grown with the phase-out of MTBE. But arguably the bulk of ethanol use at present is to replace fossil fuel used in transportation, which is what our model assumes. Note also that the perfect substitution assumption allows gasoline and ethanol to be blended in a continuum of proportions over a broad range, which is constrained only by the engine technology available in the transportation fleet. Until recently, only up to 10 percent of ethanol could be legally blended into gasoline for conventional engines, and this E10 blend is the most widely available to consumers. Thus, as long as $x_e \leq 0.1x_f$ (which is the case for current production levels), ethanol and gasoline may be considered perfect substitutes. Ethanol use in excess of this "blend wall" will require some structural changes in the transportation infrastructure, which are being actively considered by US policymakers.[9] Thus, as the blend wall issue is resolved (to deal, *inter alia*, with the full set of objectives envisioned by EISA), the domain for which our perfect substitutability assumption is appropriate is also expected to expand.

2.2. Demand

We assume a domestic population of consumers who have quasi-linear preferences. As noted earlier, consumers' utility depends upon three private goods: fuel, 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. Quasi-linear preferences permit heterogeneous individual preferences to be exactly aggregated into a single representative agent's preference ordering and allow for an internally consistent welfare analysis that is independent of the distribution of income/endowments. The assumption of separability between the utility derived from fuel consumption and that derived from corn consumption means that there are no demand side interactions between these goods; given the interaction on the supply side, this assumption is not very restrictive and seems plausible.[10] The representative consumer's utility is thus written as[11]

$$U = y+\phi(D_f)+\theta(D_c)-\sigma(x_g+\lambda x_e) \tag{3}$$

where y represents the consumption of the composite commodity (the numeraire), and the vector (D_f,D_c) represents the consumption of fuel and corn.[12] The standard assumption of quasiconcavity of the utility function in (y,D_f,D_c), given quasilinearity implies 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 (if ethanol is less polluting than gasoline per energy unit, as commonly presumed, then $\lambda < 1$).

The US consumer demand for fuel is derived from maximizing the utility function in (3), 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 $D_f(p_f)=(\phi')^{-1}(p_f)$. The domestic consumer demand for corn as food or feed is similarly obtained maximizing the utility function in (3), 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. Export of ethanol is unlikely because it is widely believed that the US corn-based technology is less efficient than Brazilian

[9] Such adaptive measures include an increase in the number of flex-fuel vehicles capable of using E85 fuel (an 85 percent blend of ethanol with gasoline), or the large-scale implementation of the recent Environmental Protection Agency (EPA) waivers allowing for E15 fuel (a 15 percent blend of ethanol with gasoline) in light-duty motor vehicles built after 2001.

[10] The assumption of quasi-linearity implies that no income affects are present in the consumption for fuel or corn. This assumption does not significantly alter results and seems plausible for a representation of a large economy which has many goods. Preferences are still ordinal, in that any positive monotonic transformation of the utility function represented in (3) would yield the same demand structure and the same welfare results.

[11] For pollution that has global ramifications – such as greenhouse gases – the negative externality depends upon global emissions. Our model ignores that, partly to avoid the inevitable issues that arise as to whether the policy setting between nations is cooperative or non-cooperative. Recognizing the impact foreign emissions have on domestic welfare and the leakage effects associated with domestic policy would, absent a cooperative solution, reduce the incentives for the domestic government to control emissions.

[12] The specification of the utility function maintains the perfect substitution assumption between ethanol and gasoline discussed in the previous section. As noted by a reviewer, whereas this assumption appears quite legitimate here, issues of consumer heterogeneity might become relevant when considering biofuel levels beyond the corn–ethanol mandate. Anderson [1] finds evidence of such heterogeneity of household preferences for E85 as a substitute for E10, and Salvo and Huse [23] find similar results for Brazil.

sugar-cane-based production. Conversely, neglecting imports of ethanol is justified by the existence of the \$0.54/gal import duty, which is effectively acting as a prohibitive tariff.[13] As for the traded commodities, the model assumes that, under free trade, the United States imports oil and exports corn.[14] Because in the welfare analysis of this article 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 article, we follow the convention by which the overbar denotes foreign variables. The ROW's import demand for corn is written as $\overline{D}_c(\overline{p}_c)$, where $\overline{p}_c$ is the net price in the foreign market. Similarly, we let $\overline{S}_o(\overline{p}_o)$ denote the ROW's export supply of oil to the United States, where $\overline{p}_o$ is the foreign price of oil. We assume that the ROW supply of oil is upward sloping and the ROW demand for corn is downward sloping, that is $\overline{S}_o' > 0$ and $\overline{D}_c' < 0$. Thus, in our model the United States is a "large country," an appealing condition given the sheer size of US oil imports and corn production and exports. This means that the United States has market power vis-à-vis these products, and that biofuel policies which impact trade flows will have terms-of-trade effects that are potentially quite important from a welfare perspective. The ability to include such terms-of-trade effects in the evaluation of biofuel policy instruments represents a major and distinctive contribution of this article.

3. Equilibrium

Before characterizing the competitive equilibrium of the model, a brief discussion of the policy setting is in order. Given our assumed endogeneity of world oil and corn prices, and the externality due to fuel consumption, there are three ways in which government intervention can increase domestic welfare. First, the endogenous export price for corn means that the United States can gain by restricting corn exports, which is the standard terms of trade argument for trade restrictions. Next, there are two possible channels through which oil import restrictions could benefit the United States: (i) the restrictions on imports lower world oil prices, and (ii) US national security may be undermined by oil imports, even if world prices were exogenous.[15] 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 (i.e., a "carbon tax").

If these three policies were implemented, then there would be no welfare-increasing rationale for other policies, such as ethanol subsidies or mandates. But some of these policies are clearly not feasible. The US constitution forbids export taxes, for example, and international commitments through the WTO constrain other border policies (as well as some domestic policies), at least in principle.[16] It follows that, from the perspective of domestic welfare, the relevant policy context is that of a second-best situation. It is therefore possible that policies such as ethanol mandates or subsidies, which indirectly affect trade volumes and pollution, might improve domestic welfare, even though these indirect policies will not be able to achieve the first-best solution. Because in this article we wish to focus on ethanol policies, we also assume that there are no other domestic taxes or subsidies in place. Hence

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.

3.1. Corn and ethanol markets

As discussed earlier, the market supply function of corn is: $X_c = (C')^{-1}(p_c) \equiv S_c(p_c)$. There are three uses for domestic corn output: domestic consumption by households,[17] with demand $D_c(p_c)$, exports, with demand $\overline{D}_c(\overline{p}_c)$, and ethanol

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

[14] 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.

[15] If national security is undermined by reliance on imported oil, this could be reflected in the "utility" function by having utility negatively related to imports. As we explain in Section 5, this effect is very similar to the terms of trade effect and provides an additional rationale as to why reducing imports can be beneficial.

[16] A domestic consumption tax on oil, coupled with a production subsidy for domestic oil producers, is equivalent to an oil import tariff. Similarly, a tax on domestic corn production and a subsidy to domestic corn consumption is equivalent to an export tax on corn. Hence, constraining border policies entails implicit constraints on domestic policies.

[17] 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.

production. For any given amount of corn x_c devoted to ethanol production, equilibrium in the corn market must satisfy

$$S_c(p_c) = D_c(p_c) + \overline{D}_c(p_c) + x_c \tag{4}$$

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

$$Q(p_c) \equiv S_c(p_c) - D_c(p_c) - \overline{D}_c(p_c) \tag{5}$$

Clearly, $Q'(p_c) > 0$. Also, using (1), we get the inverse ethanol supply curve:

$$p_e^s(x_e) = \frac{p_c(x_e/\alpha)}{\alpha} + w_e \tag{6}$$

where $p_c(\cdot) \equiv Q^{-1}(\cdot)$. Thus the derived inverse ethanol supply curve implied by our model is upward sloping, $dp_e^s/dx_e = [\alpha^2 Q'(p_c)]^{-1} > 0$ (despite free entry into the ethanol industry).

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 $\overline{S}_o(p_o)$. The per-unit production cost of unblended gasoline, which, assuming perfect competition, is the selling price of gasoline to refiners, can be written as

$$\left(\frac{p_o}{\beta} + w_g\right) = p_g \quad \Leftrightarrow \quad p_o = (p_g - w_g)\beta \tag{7}$$

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:

$$x_g = \beta[\overline{S}_o(p_o) + S_o(p_o)] \equiv \psi(p_g - w_g) \tag{8}$$

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

$$\frac{dx_g}{dp_g} = \psi' = \beta^2 \left[\overline{S}'_o(p_o) + S'_o(p_o)\right] > 0 \tag{9}$$

4. Market impacts of policies

The main objective of the article is to analyze the welfare implications of various biofuel policies. With that in mind, it is desirable to first consider the equilibrium conditions and the market impacts (comparative statics) of these policies. These impacts are interesting in their own right and also permit one to compare some positive implications of our analysis with those of other models, such as de Gorter and Just [5,6]. But the results of the analysis of this section are also used later as they provide the basis for the normative analysis that follows. We start by considering the effects, in a competitive equilibrium, of a fuel tax and ethanol subsidy.[18]

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 [20]. 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:

$$\begin{aligned} p_g^s(x_g) &= p_f(x_g + x_e) - t \\ p_e^s(x_e) &= p_f(x_g + x_e) - t + b \end{aligned} \tag{10}$$

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

$$\begin{bmatrix} dt \\ -db \end{bmatrix} = \frac{-1}{r_1 r_2 r_3 N} \begin{bmatrix} (r_1 + r_3) r_2 & r_2 r_3 \\ -r_1 r_2 & r_1 r_3 \end{bmatrix} \begin{bmatrix} dx_g \\ dx_e \end{bmatrix} \tag{11}$$

[18] 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 $(b - t)$.

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
$\frac{\partial p_g}{\partial t}=\frac{\partial x_g/\partial t}{\psi'}=-r_1<0$	$\frac{\partial x_g}{\partial t}=-r_1\psi'<0$
$\frac{\partial p_f}{\partial t}=\frac{\partial x_f/\partial t}{D'}=(r_2+r_3)>0$	$\frac{\partial x_f}{\partial t}=(r_2+r_3)D'<0$
$\frac{\partial p_e}{\partial t}=\frac{\partial x_e/\partial t}{\alpha^2 Q'}=-r_1<0$	$\frac{\partial x_e}{\partial t}=-r_1\alpha^2 Q'<0$
$\frac{\partial p_g}{\partial b}=\frac{\partial x_g/\partial b}{\psi'}=-r_2<0$	$\frac{\partial x_g}{\partial b}=-r_2\psi'<0$
$\frac{\partial p_f}{\partial b}=\frac{\partial x_f/\partial b}{D'}=-r_2<0$	$\frac{\partial x_f}{\partial b}=-r_2 D'>0$
$\frac{\partial p_e}{\partial b}=\frac{\partial x_e/\partial b}{\alpha^2 Q'}=(r_1+r_3)>0$	$\frac{\partial x_e}{\partial b}=(r_1+r_3)\alpha^2 Q'>0$

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

$$r_1\equiv\frac{-D_f'}{N},\quad r_2=\frac{\alpha^2Q'}{N},\quad r_3\equiv\frac{\psi'}{N},\quad \sum_{i=1}^{3}r_i=1 \tag{12}$$

Inverting yields

$$\begin{bmatrix} dx_g \\ dx_e \end{bmatrix}=(-N)\begin{bmatrix} r_1r_3 & -r_2r_3 \\ r_1r_2 & (r_1+r_3)r_2 \end{bmatrix}\begin{bmatrix} dt \\ -db \end{bmatrix} \tag{13}$$

The impact of the fuel tax or the ethanol subsidy on the prices and quantities of gasoline, ethanol and fuel, as derived in Eqs. (11) and (13), 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

As noted, a central element of the US biofuels policy concerns the use of quantitative "mandates" on the minimum amount of biofuels to be blended into transportation fuel. A number of details are relevant in this context (see, e.g., [24]), but a brief account is as follows. EISA specifies target quantities of various biofuels (cellulosic ethanol, biodiesel and advanced biofuels) as well an overall renewable fuel quantity that implicitly determines how much corn-based ethanol can be used to meet the mandates.[19] The EPA is responsible for enforcing the volume mandates, and it does so by first calculating the RFS blending percentages by dividing the volume of renewable fuels that are mandated by total expected US fuel use. Because commercial production of cellulosic ethanol and advanced biofuels is not meeting expectations, at present corn-based ethanol (up to the allowable limit) appears to be the only effective way to meet the aggregate biofuel mandate, and so in what follows we will focus on the corn–ethanol portion of the biofuel mandates. For each year, the RFS percentage is used to determine the individual renewable volume obligations (RVOs) of "obligated parties" (e.g., fuel refiners and blenders): the RVO for each obligated party is the product of the percentage standard by the firm's annual fuel sales. To ensure that such obligations are met, a Renewable Identification Number (RIN) system is used. RINs are unique identifiers assigned to ethanol batches at production and follow such ethanol through the marketing chain. RINs are "separated" from ethanol only when it is blended with gasoline, and can then be used by obligated parties to show that in fact they met their RVOs. Blenders can meet the RIN requirement by (i) buying a sufficient amount of ethanol to satisfy their RVOs or, alternatively, (ii) buy RINs from other obligated parties who are using more ethanol than what they are mandated (and thus have an excess of RINs).

The bottom line is that, in aggregate, a given minimum amount (volume) of biofuel must be sold annually as part of the fuel supply, irrespective of the additional costs incurred. In a competitive equilibrium, such a mandate may or may not be binding. If it is not binding, then in our deterministic setting the mandates will have no effects, and the analysis of the previous section applies. But when, at the prevailing prices and tax/subsidies, competitive profit maximizing blenders would want to use a lower amount (lower percentage) of biofuels than that specified by the mandates, then the mandates

[19] In 2010, for example, the total renewable fuel mandate specified by EISA was 12.95 billion gallons (1.7 billion gallons of which to be accounted for by biofuels other than corn-based ethanol); the overall biofuel mandate is set to increase to 36 billion gallons by 2022 (with corn-based ethanol capped at 15 billion gallons).

bind, and a mechanism must be put in place that forces these blenders to comply with the mandates. In such a case the competitive equilibrium conditions must be adjusted accordingly. The model we set up essentially represents compliance strategy (i) above, i.e., each obligated party buys sufficient ethanol to meet the mandated percentage standard for the fuel they sell. Thus, their (marginal) cost of producing fuel, when the mandates bind, is a weighted average of the supply prices (including taxes or subsidies) of ethanol and gasoline, where the weight on ethanol reflect the percentage standard imposed by the EPA. An alternative approach would be to represent compliance strategy (ii) and explicitly model the RIN market. Apart from establishing the equilibrium price of RINs, it is apparent that this alternative approach would have identical equilibrium implications to our modeling structure, in a competitive setting.[20]

4.2.1. Quantity mandates: A novel interpretation

A binding mandate means that blenders, who sell fuel, must use more ethanol than would otherwise be profitable. Hence, the arbitrage condition for relating ethanol, gasoline and fuel prices developed in the previous sections no longer applies. Rather, the firm's costs of supplying fuel will depend upon the percentage standard calculated by EPA. Let κ represent this blending percentage, so the firm is obligated to use κ units of ethanol for each gallon of fuel sold. Hence, the cost to the firm of providing a gallon of fuel is $\kappa(p_e^s - b) + (1-\kappa)p_g^s$ which, under competitive conditions must equal the fuel price consumers pay less the tax on fuel, that is $(p_f - t)$.[21] Thus, with an exogenous mandate the equilibrium condition may be written as

$$[p_f(x_g + x_e^M) - t] = \kappa[p_e^s(x_e^M) - b] + (1-\kappa)p_g^s(x_g)$$

Because $\kappa = x_e^M/(x_g + x_e^M)$, this equation can be equivalently expressed as the zero profit condition that must hold in a competitive equilibrium with free entry:

$$\Gamma \equiv [p_f(x_g + x_e^M) - t](x_g + x_e^M) - p_g^s(x_g)x_g - [p_e^s(x_e^M) - b]x_e^M = 0 \tag{14}$$

Specifically, with a binding mandate the zero profit condition in (14) determines the equilibrium gasoline quantity $x_g(x_e^M, b, t)$; given that, the fuel price is demand-determined via the inverse demand function $p_f(\cdot)$, and the ethanol and gasoline prices are supply-determined via the inverse supply functions $p_e^s(\cdot)$ and $p_g^s(\cdot)$. Essentially, to comply with a binding mandate, blenders must procure more ethanol than they would desire at existing prices, and hence make a loss on that portion of their business. For them to stay in business, it must be that such a loss is compensated by a profit in the acquisition of gasoline. In fact, the zero-profit condition in (14) implies that the positive and negative returns from input procurement in the production of fuel are exactly offset:

$$[(p_e - b) - (p_f - t)]x_e^M = (p_f - t - p_g)x_g \tag{15}$$

Thus, with a strictly binding mandate the arbitrage price conditions in (10) do not hold and, from (15), it follows that $(p_e - b) > (p_f - t) > p_g$. Indeed, another way to view the zero profit condition in (14) is to note that, with a binding mandate, the equilibrium after-tax fuel price is a weighted average of the net prices of ethanol and gasoline, as also articulated in de Gorter and Just [6].[22]

For uniqueness of the solution to (14) it suffices that $\partial\Gamma/\partial x_g$, evaluated at $\Gamma = 0$, always has the same sign, whereas stability requires that, around equilibrium, excess profits fall as x_g increases.[23] Thus, the equilibrium $x_g(x_e^M, b, t)$ is unique and stable if

$$\left.\frac{\partial \Gamma}{\partial x_g}\right|_{\Gamma=0} = MR_f - t - MC_g < 0 \tag{16}$$

where $MR_f \equiv p_f + x_f(dp_f/dx_f)$ denotes the marginal revenue associated with an increase in fuel sales, and $MC_g \equiv p_g + x_g(dp_g/dx_g)$ denotes the increase in expenditures on gasoline due to an increase in gasoline sales. Note that around a point where the mandate just binds, $(p_f - p_g - t) = 0$ and hence (16) must hold. We assume that this stability conditions holds for all binding combinations of (x_e^M, b, t) (note that a sufficient condition is that the demand for fuel is inelastic).

With a unique solution, consider any initial situation (t^0, b^0, x_e^M) in which the mandate binds. Denote the solution to (14) by x_g^0, with corresponding prices given by $p_f^0 = p_f(x_g^0 + x_e^M)$, $p_g^0 = p_g^s(x_g^0)$ and $p_e^0 = p_e^s(x_e^M)$, where $(p_e^0 - b^0) > (p_f^0 - t^0) > p_g^0$. Now

[20] Theoretically, it is readily shown that, under perfect information, there is a 1–1 correspondence between the aggregate mandate level and the blending percentage, given market stability. With RINs, the equilibrium price of fuel to consumers would be the same as if blenders acquired the necessary ethanol to meet the percentage standard directly. As in our approach, the supply prices of ethanol and gasoline would differ, but from the blenders perspective, the cost of producing fuel using gasoline – which would include the cost of the number of RINs required to do so – would equal the net cost of producing fuel from ethanol (which would reflect the supply price of ethanol less the value of RINs earned by using ethanol). The price of RINs in this setup would be proportional to the difference between the supply prices of ethanol and gasoline in our setup, and hence can readily be calculated.

[21] The zero profit condition, a hallmark of equilibrium under perfect competition, of course also applies to the previous section's case when the mandate is not binding—it is readily verified that the arbitrage conditions in (10) imply just that.

[22] Ando et al. [2], by contrast, model ethanol mandates as quantity constraints on the fuel industry (meeting the mandate is essentially treated as a large fixed initial cost). Because the underlying market structure is not defined, it is unclear how blenders (who would lose money under marginal cost pricing) could be made to comply with the mandates in such a setting.

[23] We assume that fuel demand curves slope downward and oil supply curves slope upward, so this condition is the same as the Walrasian stability condition in the fuel market, given x_e^M and the equilibrium rule in (14).

consider tax and subsidy changes (Δb,Δt). If these changes are restricted so that (14) continues to hold at (x_g^0,x_e^M), then we must have

$$\Delta t(x_g^0+x_e^M)=\Delta b x_e^M \tag{17}$$

Furthermore, the requirement that the mandate continues to bind implies

$$\Delta b \le (p_e^0-b^0-p_g^0) \tag{18}$$

Note that (17) also implies that these changes (Δb,Δt) leave net government tax revenues unchanged. Hence

Lemma 1. *From an initial situation (x_e^M,b^0,t^0) such that the ethanol mandate is binding, any change in the ethanol subsidy and fuel tax that is budget-neutral and such that the mandate still binds leaves the equilibrium unchanged.*[24]

More generally, we can claim the result in Proposition 1. We will show later that this result is extremely valuable in the analysis to welfare-rank the mandate and subsidy instruments.

Proposition 1. *An ethanol mandate,* per se*, is fully equivalent to a combination of an ethanol subsidy and a fuel tax that are revenue neutral.*

For the proof, suppose that $b^0=t^0=0$ and that the mandate x_e^M is binding such that (14) holds and $p_e^0-p_g^0>0$. Now consider introducing the following ethanol subsidy and fuel tax: $b \equiv (p_e^0-p_g^0)$ and $t=[x_e^M/(x_g^0+x_e^M)](p_e^0-p_g^0)$. By construction such changes are revenue-neutral and leave the zero profit condition satisfied and hence, from Lemma 1, the initial equilibrium is unchanged. But at this new subsidy-tax combination, the individual arbitrage conditions hold, that is $(p_e-b-p_g)=0$ and $(p_f-t-p_g)=0$. Hence, if the mandate were relaxed, the equilibrium would remain unchanged (i.e., the given tax and subsidy combination can support an ethanol production exactly equal to x_e^M).

4.2.2. Quantity mandates and comparative statics

The equilibrium condition (14) that holds with a binding mandate, in conjunction with the stability conditions discussed earlier, can be used to illustrate how changes in the ethanol subsidy, the fuel tax, or the mandate itself affect gasoline production and fuel consumption, as well as the mandate-equivalent taxes and subsidies. From (14) we find $\partial\Gamma/\partial b=x_e^M>0$, $\partial\Gamma/\partial t=-x_f<0$ and

$$\frac{\partial \Gamma}{\partial x_e^M}=(MR_f-t)-(MC_e-b) \tag{19}$$

where MR_f was defined earlier and $MC_e \equiv p_e+x_e(dp_e/dx_e)$ is the increase in expenditures on ethanol due to an increase in ethanol sales. Using the definitions from (12), the expressions in (16) and (19) can be rewritten as

$$\left.\frac{\partial \Gamma}{\partial x_g}\right|_{\Gamma=0}=-\frac{H}{N}<0, \quad H \equiv \frac{x_f}{r_1}+\frac{x_g}{r_3}+N(p_g+t-p_f)>0 \tag{20}$$

$$\frac{\partial \Gamma}{\partial x_e^M}=-\frac{K}{N}<0, \quad K \equiv \frac{x_f}{r_1}+\frac{x_e}{r_2}+N\Big[(p_e-b)-(p_f-t)\Big]>0 \tag{21}$$

The sign of H follows from the stability condition, whereas that of K follows from the fact that, when the mandate binds, all terms are positive.

From the foregoing the following comparative statics results can be established.[25] Given a binding mandate: (i) an ethanol subsidy sufficiently small so that the mandate still binds raises gasoline production and fuel consumption, lowers fuel prices, and increases pollution; (ii) a fuel tax sufficiently small so that the mandate continues to bind lowers gasoline production and fuel consumption, raises fuel prices and reduces pollution; (iii) an increase in a binding mandate is equivalent to – in the absence of the mandate – an increase in the ethanol subsidy and the fuel tax that is budget neutral; (iv) although one should expect that increasing a binding mandate raises the blended fuel prices, and thus reduces total consumption, this particular comparative statics effect is actually indeterminate. If the supply of ethanol is more elastic than the supply of gasoline, then over some domain an increasing ethanol mandate may in fact lower the price of fuel and raise total fuel consumption.

5. Welfare implications of policy

The utility function in (3) 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, welfare W can

[24] If the market for RINs were modeled explicitly, then this revenue neutral change in the ethanol subsidy and fuel tax would affect the equilibrium price of RINs, but would not affect any real (quantity) variable.

[25] Results (i) and (iv) are discussed in some detail by de Gorter and Just [6].

be represented as[26]

$$W=[I-C(D_c+\overline{D}_c+x_c)-\Omega(S_o)-w_e x_e-w_g x_g+(p_c\overline{D}_c-p_o\overline{S}_o)]+\phi(x_g+x_e)+\theta(D_c)-\sigma(x_g+\lambda x_e) \tag{22}$$

In this equation, I is the aggregate endowment of the numeraire, $C(D_c+\overline{D}_c+x_c)$ 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 $(p_c\overline{D}_c-p_o\overline{S}_o)$ 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 trade, prices affect domestic welfare because price changes redistribute wealth between domestic and foreign agents. In particular, given the large country assumption noted earlier, insofar as its biofuel policies affect world prices of corn and oil they allow the United States to extract some market power rent via the terms-of-trade effects.

5.1. Welfare with two policy instruments: fuel tax and ethanol subsidy

We seek to characterize conditions under which welfare is maximized, i.e., $dW=0$. The strategy we follow is to derive the conditions that identify the (second-best) optimal levels of gasoline and ethanol, while accounting for all of the relevant agents' optimality and competitive equilibrium conditions implied by the model. Whereas the conditions we derive pertain to the constrained socially optimal levels of (x_g,x_e), we will characterize them in terms of the corresponding optimal fuel tax and ethanol subsidy levels. Taking the total differential of (22) yields

$$\begin{aligned}dW=&\phi'(dx_g+dx_e)+\theta' dD_c-C'(dD_c+d\overline{D}_c+dx_c)-\Omega' dS_o\\&-w_e dx_e-w_g dx_g+p_c d\overline{D}_c+\overline{D}_c dp_c-p_o d\overline{S}_o-\overline{S}_o dp_o-\sigma'(dx_g+\lambda dx_e)\end{aligned} \tag{23}$$

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 recalling that the assumed production structure implies $dx_g=\beta(dS_o+d\overline{S}_o)$ and $dx_e=\alpha\, dx_c$, we obtain

$$dW=\left[p_f-\frac{p_o}{\beta}-w_g-\sigma'\right]dx_g+\left[p_f-w_e-\frac{p_c}{\alpha}-\lambda\sigma'\right]dx_e+\overline{D}_c\, dp_c-\overline{S}_o\, dp_o \tag{24}$$

From the zero profit condition for oil refining and ethanol production (rents are transferred to the corn market), the price received by the sellers of gasoline is $p_g^s=p_o/\beta+w_g$, and the price received by the sellers of ethanol is $p_e^s=p_c/\alpha+w_e$. Using these price conditions, Eq. (24) becomes

$$dW=[t-\sigma']dx_g-[b-t+\lambda\sigma']dx_e+\overline{D}_c\, dp_c-\overline{S}_o\, dp_o \tag{25}$$

where the "effective" tax on fuel and "effective" subsidy to ethanol are defined by[27]

$$\begin{aligned}t&\equiv p_f-p_g^s\\b&\equiv p_e^s-(p_f-t)\end{aligned} \tag{26}$$

Recall that, with no domestic or border policies in the corn or oil market, corn price is in 1–1 correspondence with ethanol output and oil supply is in 1–1 correspondence with the price of oil. Hence, we can write ethanol supply as a function of corn price as $x_e=\alpha Q(p_c)$, where $Q(p_c)$ is the supply of corn to the ethanol industry in Eq. (5). From this we obtain $dx_e=\alpha Q'\, dp_c$, implying $dp_c=(1/\alpha Q')\, dx_e$. Similarly, we can write unblended gasoline supply as a function of oil price, and therefore as a function of gasoline price, as in Eq. (8). From (8) we obtain $dx_g=\psi'\, dp_g$, and from $p_o=(p_g-w_g)\beta$ we get $dp_o=\beta\, dp_g$, and so $dp_o=(\beta/\psi')dx_g$. Using these equivalent representations for dp_c and dp_o, Eq. (25) can be expressed as

$$dW=\left[t-\sigma'-\frac{\beta\overline{S}_o}{\psi'}\right]dx_g-\left[b-t+\lambda\sigma'-\frac{\overline{D}_c}{\alpha Q'}\right]dx_e \tag{27}$$

In what follows we are interested in characterizing the optimality conditions for welfare maximization in the (x_g,x_e) space. Towards that end, define

$$W_g\equiv\frac{\partial W}{\partial x_g}=p_f(x_g+x_e)-p_g(x_g)-\sigma'(x_g+\lambda x_e)-\frac{\beta\overline{S}_o(p_o(x_g))}{\psi'(p_g(x_g))} \tag{28}$$

[26] While the term $p_o\overline{S}_o$ represents the economic cost of oil imports (given the constraint of no oil tariffs, $p_o=\overline{p}_o$), it can more broadly be interpreted as including the national security costs of relying on imported oil. That is, since p_o depends on $\overline{S}_o$, we could replace $p_o\overline{S}_o$ in the objective function by $H(\overline{S}_o)$, which would incorporate both the economic costs of imports as well as the national security costs. In the equations that follow, this would entail replacing the term $(p_0+\overline{S}_o/\overline{S}_o')$ by $H'(\overline{S}_o)>p_o$. Nothing substantive would be altered by making this substitution.

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

$$W_e \equiv \frac{\partial W}{\partial x_e} = p_f(x_g+x_e) - p_e(x_e) - \lambda\sigma'(x_g+\lambda x_e) + \frac{\overline{D}_c(p_c(x_e))}{\alpha Q'(p_c(x_e))} \tag{29}$$

The study of policies' optimality necessarily rests on some (weak) regularity conditions that must be satisfied by the welfare function. Consider the second (partial) derivatives of the welfare function in the variables x_g and x_e:

$$W_{gg} = \frac{1}{D_f'} - \frac{1}{\psi'} - \sigma'' - \left\{ \frac{(\psi')^2[\overline{S}_o'/(S_o'+\overline{S}_o')] - [\overline{S}_o/(S_o+\overline{S}_o)]\psi''\psi}{(\psi')^3} \right\}$$

$$W_{ee} = \frac{1}{D_f'} - \frac{1}{\alpha^2 Q'} - \lambda^2\sigma'' + \left\{ \frac{\overline{D}_c' Q' - \overline{D}_c Q''}{\alpha^2 (Q')^3} \right\}$$

$$W_{eg} = W_{ge} = \frac{1}{D_f'} - \lambda\sigma'' \tag{30}$$

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 conditions $W_{ee} < 0$ and $W_{eg} < 0$ that are required by this assumption are standard curvature properties, 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.[28]

The optimality conditions in (x_g,x_e) space can be illustrated by drawing the contours $W_g=0$ and $W_e=0$. The concavity and substitute conditions from Assumption 2 guarantee that $dx_g/dx_e|_{W=0} = -W_{ee}/W_{eg} < 0$ and $dx_g/dx_e|_{Wg=0} = -W_{eg}/W_{gg} < 0$. 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 Fig. 1.

The optimal solution in Fig. 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 (11) and (13) choosing (x_g,x_e) is equivalent to choosing (t,b). Because $dW=0$ at this second-best solution, then from (27) 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*

$$t^* = \sigma' + \frac{\beta\overline{S}_o}{\psi'} > 0 \text{ and } b^* = \frac{\overline{D}_c}{\alpha Q'} + (1-\lambda)\sigma' + \frac{\beta\overline{S}_o}{\psi'} \tag{31}$$

Note that both t^* and b^* will be positive, provided $\lambda \le 1$ (i.e., ethanol does not pollute more than gasoline). As discussed earlier, the reasons for intervention are the externality and the impact of domestic policy on our import/export prices.[29] 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 2. *If the tax t applies only to gasoline, so that the ethanol subsidy represents a net subsidy, the optimal policy is* $t^* = \sigma' + (\beta\overline{S}_o/\psi') > 0$ *and* $\hat{b} = (\overline{D}_c/\alpha Q') - \lambda\sigma'$.

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 [6] and Holland et al. [15], 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.

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 Fig. 1 cannot be reached.[30] We now turn to a welfare comparison of these two instruments when the tax on fuel is not an active policy tool.

[28] For example, suppose that $S_o(p_o) = k\overline{S}_o(p_o)$ for some positive scalar k. Then sufficient conditions for Assumption 2 to hold are: $\sigma'' \ge 0$, $Q'' \ge 0$ and $\psi(\cdot)$ is logconcave.

[29] 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.

[30] 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.

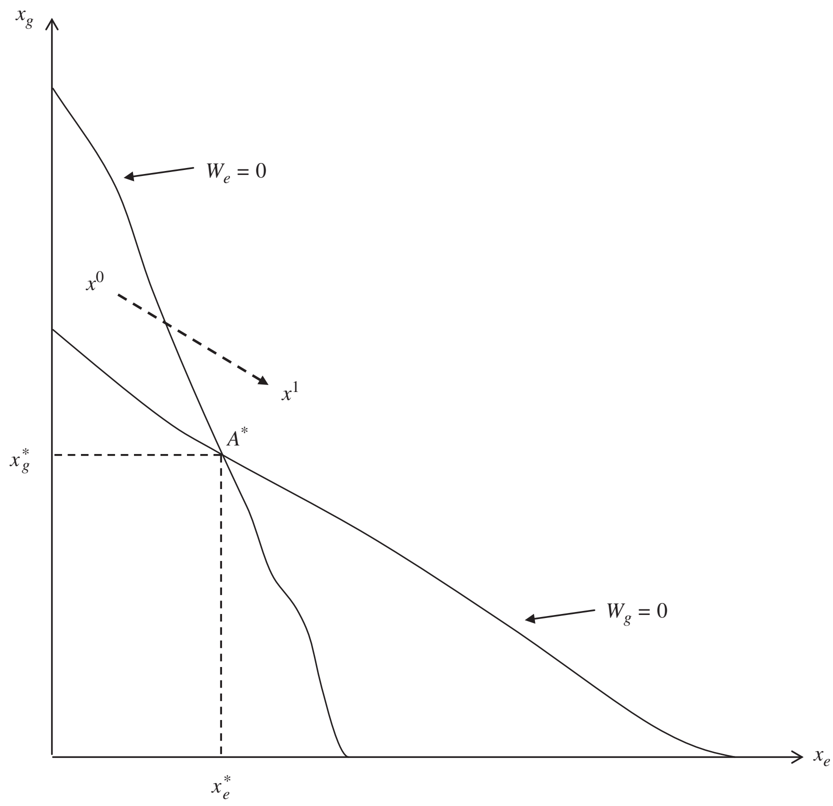

Fig. 1. Welfare in ethanol–gasoline space.

5.2. *Welfare when ethanol subsidies are the only policy instrument*

Political considerations may make it very difficult to consider increasing the fuel (or gasoline) tax, despite the economic merits of doing so. US fuel taxes are well below those of Europe, and the 18.4 cents per gallon Federal gasoline excise tax has remained unchanged since 1993. On the other hand, a policy in which the benefits are concentrated in a smaller group and whose costs are less transparent – as is the case with ethanol mandates or even subsidies – is likely to generate greater political support. For this reason, it is of considerable interest to consider "optimal" policy under the constraint it must be directed at the ethanol industry.

As shown earlier, ethanol subsidies affect both gasoline usage and ethanol usage. Substituting (13) into (27) yields:

$$dW = N\{-W_g[r_1 r_3\, dt + r_2 r_3\, db] + W_e[(r_1+r_3)r_2\, db - r_1 r_2\, dt]\} \tag{32}$$

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

$$\frac{\partial W}{\partial b} = N\left[W_e(r_1+r_3)r_2 - W_g r_2 r_3\right] \quad = N(r_1+r_3)r_2\left[W_e + \eta W_g\right] \tag{33}$$

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:

$$\eta \equiv \frac{\partial x_g/\partial b}{\partial x_e/\partial b} = \frac{-r_3}{r_1+r_3} = \frac{-\psi'}{\psi' - D_f'} \tag{34}$$

Eq. (33) 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 Fig. 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 Fig. 1, where x^0 represents the *laissez faire* point).

The optimal ethanol subsidy must solve $\partial W/\partial b=0$ and thus, from (33), $W_e+\eta W_g=0$. Using prior definitions, with an exogenous tax t this requires:

$$\left(\frac{\overline{D}_c}{\alpha Q'} - \lambda\sigma' + p_f(x_e+x_g) - p_e(x_e)\right) + \left(\frac{-\psi'}{\psi' - D_f'}\right)\left(p_f(x_e+x_g) - p_g(x_g) - \sigma' - \frac{\beta \overline{S}_o}{\psi'}\right) = 0 \tag{35}$$

The solution to the constrained welfare optimum, denoted $[\tilde{x}_e(t),\tilde{x}_g(t)]$, is found using Eq. (35) and the arbitrage equation $p_f(x_e+x_g)-p_g(x_g)-t=0$. 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" ($W_e<0$), 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 $t<\sigma'+\beta\overline{S}_o/\psi'$.[31] Finally, the optimal subsidy is given, definitionally, by $\tilde{b}(t)=p_e(\tilde{x}_e)-p_f(\tilde{x}_g+\tilde{x}_e)+t$. 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*

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

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.

5.3. Welfare when mandates are the only policy instrument

We turn now to the welfare implications of mandates. From (27), and recalling (26), when the mandate is the only active policy instrument we have:

$$\frac{dW}{dx_e^M}=\left[(p_f-p_g)-\sigma'-\frac{\beta\overline{S}_o}{\psi'}\right]\frac{\partial x_g}{\partial x_e^M}+\left[(p_f-p_e)-\lambda\sigma'+\frac{\overline{D}_c}{\alpha Q'}\right] \tag{36}$$

Differentiating (15), and recalling earlier definitions, the impact of a binding ethanol mandate on gasoline sales is

$$\frac{dx_g}{dx_e^M}=-\frac{\psi'+\kappa\psi'(-D_f'/\alpha^2Q')+(1-\kappa)(p_e-p_g)(-D_f'\psi'/x_f)}{\psi'+(-D_f')(1-\kappa)-\kappa(p_e-p_g)(-D_f'\psi'/x_f)} \tag{37}$$

where as before, $\kappa\equiv(x_e^M/x_f)\in(0,1)$ 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, $p_f=\kappa p_e+(1-\kappa)p_g$, implying $(p_e-p_f)=(1-\kappa)(p_e-p_g)$ and $(p_f-p_g)=\kappa(p_e-p_g)$.

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 (34) and (37), when evaluated at the same point (x_g,x_e),

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

Thus, for a given increase in ethanol usage, gasoline usage declines more under the mandate. The reason is that, while both instruments encourage substituting ethanol for gasoline, the mandate also implicitly entails a tax on fuel. Thus, if the mandate and subsidy are set to yield the same ethanol output, the mandate will yield lower gasoline use (lower p_g) and lower aggregate fuel consumption (higher p_f).

Turning to the first order conditions, we have

Proposition 4. *If the only feasible policy is an ethanol mandate, then a binding mandate will increase welfare if*:

$$\left.\frac{dW}{dx_e^M}\right|_{p_f=p_e}=\frac{\overline{D}_c}{\alpha Q'}-\lambda\sigma'+\left(\sigma'+\frac{\beta\overline{S}_o}{\psi'}\right)\left[\frac{\psi'+\kappa\psi'(-D_f'/\alpha^2Q')}{\psi'+(1-\kappa)(-D_f')}\right]>0$$

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

The proof of this proposition follows from (36), using (37), and evaluating at the laissez-faire point $p_f = p_g = p_e$.[32] 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 3. *If it would be optimal to tax ethanol (i.e., $b^* < 0$) when only ethanol subsidies can be used, it may still be optimal to have a binding mandate when mandates are the only feasible policy.*

This lemma follows from comparing the results of Propositions 3 and 4. Specifically, the expression in Proposition 4 coincides with that for b^* in Proposition 3 when $\kappa = 0$. Thus, if it is optimal to tax ethanol ($b^* < 0$) and $\kappa = 0$, then a positive mandate would not increase welfare. But, the expression in Proposition 4 is monotonically increasing in κ. Furthermore, at $\kappa = 1$ the expression in Proposition 4 must be positive, provided $\lambda \leq 1$. 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. The underlying reason why the mandate differs from (and may be preferred to) the subsidy is because the mandate entails an implicit tax on gasoline (or fuel), which would be part of the second best policy when both ethanol subsidies and gasoline taxes are feasible.

5.4. Comparing ethanol subsidies and ethanol mandates

For the purpose of the optimal second-best policy, it is apparent that it is better to use two instruments (fuel tax and ethanol subsidy or mandate), rather than only one of them. But, as discussed earlier, it is also of considerable interest to directly compare ethanol mandates and ethanol subsidies under the presumption that the level of the fuel tax might not be an active policy instrument. Such a ranking of restricted policies in a second-best framework is typically very difficult. In our setting, however, we are able to show that, when they are the only available policy instrument, ethanol mandates dominate ethanol subsidies. The strategy that we use to derive this welfare ranking 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. One qualification: the proof we provide presumes that the net revenue collected when both fuel taxes and ethanol subsidies are optimally chosen is positive. But it is apparent that such a condition is not very restrictive. Net revenue at such an 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

$$T^* = \sigma'(x_g + \lambda x_e) + \frac{p_o \overline{S}_o}{\varepsilon_g} - \frac{p_c \overline{D}_c}{\varepsilon_c} \tag{38}$$

where $\varepsilon_g \equiv (dx_g/dp_g)(p_g/x_g)$is the elasticity of the derived supply of gasoline and $\varepsilon_c \equiv (dQ/dp_c)(p_c/Q)$ is the elasticity of the residual supply 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 $p_o \overline{S}_o$ vastly exceeds the value of corn exports $p_c \overline{D}_c$, and the elasticity of the residual supply curve for corn is probably 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. Hence

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):

$$T \equiv t(x_g, x_e)(x_g + x_e) - b(x_g, x_e) x_e \tag{39}$$

Totally differentiating (39), and using (11), (20) and (21), implies

$$dT = -\frac{1}{N}(H\, dx_g + K\, dx_e) \tag{40}$$

where $H > 0$ and $K > 0$ were defined in (20) and (21). Hence, the iso-tax revenue condition $dT = 0$ yields $dx_g/dx_e = -K/H < 0$. That is, the iso-tax revenue curves are negatively sloped in the (x_g, x_e) space. Furthermore, Eq. (40) 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 4. *Let $S(x_g, x_e, T_i) \equiv \{(x_g, x_e) \,|\, t(x_g, x_e) x_f - b(x_g, x_e) x_e \leq T_i\}$ denote the set of points that yield at most a given tax revenue T_i. If $T_1 > T_0$, then $S(x_g, x_e, T_0) \subset S(x_g, x_e, T_1)$.*

[32] 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 right-hand-side of the expression in Proposition 4, say $-\nu$, where $\nu \equiv p_e(x_e = 0) - p_f$ represents what de Gorter and Just [7] refer to as "water" in the mandate or subsidy.

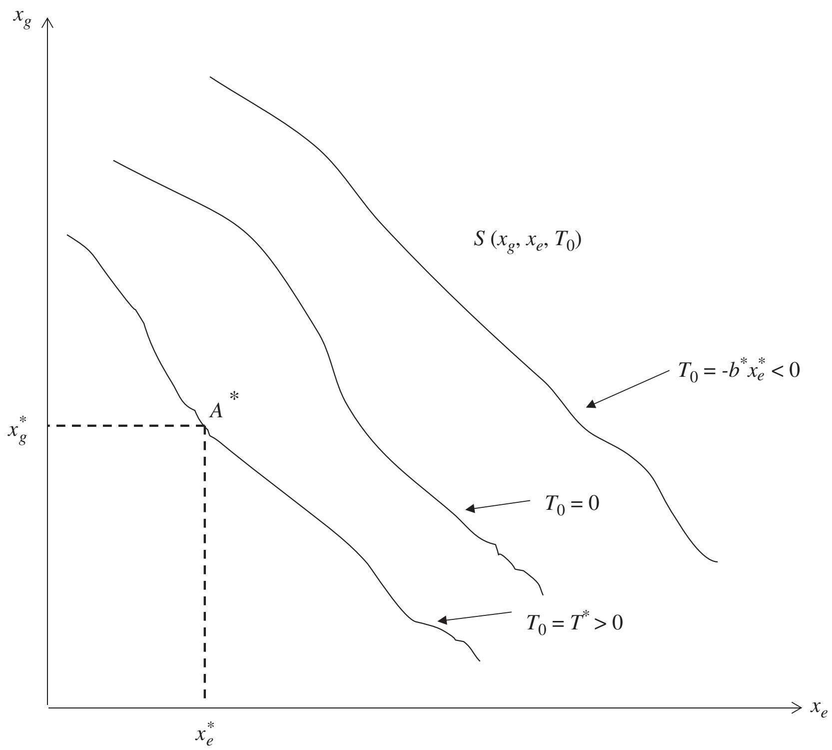

Fig. 2. Iso-tax revenue curves.

Fig. 2 illustrates these iso-tax revenue curves. The properties of these iso-tax revenue curves, in conjunction with Assumption 3, allow us to show that, according to the welfare criterion, an ethanol mandates policy dominates an ethanol subsidies policy. Specifically

Proposition 5. *Let T^* denote the net tax revenue corresponding to the optimal policy when both fuel taxes and ethanol subsidies are used. Then, if $T^* > 0$:*

(i) *If no fuel taxes are used, ethanol mandates yield higher welfare than an ethanol subsidy policy.*
(ii) *Given a mandate, increasing the fuel tax above zero will raise welfare. Assuming the ethanol mandate is adjusted optimally to the exogenous fuel tax, increases in the fuel tax raise welfare provided net tax revenue is no larger than T^*.*

The proof of this proposition, detailed in Appendix A1, relies on comparing the maximized value of the welfare function when using the instruments (b,t), subject to the constraint that the policy yield (no more than) a given tax revenue, say $\hat{W}(T_0)$. In view of Lemma 4, 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 A1, 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 and nonrenewable energy sources are expected to have significant economic consequences in the years to come and it is important that the impact of alternative policies be well understood. While there are several possible sources of renewable energy, we have focused in this article on biofuels (which for the United States essentially means corn-based ethanol), though in principle the same modeling approach could be used to study the impact of policies on other forms of renewable energy.

We reach several noteworthy and novel conclusions. In our setting, it is clear that the first best policy from a welfare maximization perspective would require three policy instruments: an import tax on oil, an export tax on corn, and a "carbon tax" on emissions from fuel consumption. But such a first-best policy is, of course, hardly feasible, and therefore in the bulk of our analysis we fully characterize the second best solution that relies on subsidizing ethanol and taxing fuel (the mix of gasoline and ethanol). This characterization emphasizes the role that a fuel tax and an ethanol subsidy might have on the terms of trade for imported oil and exported corn, via their impact on expanding the renewable fuel industry, which has potentially large welfare impacts. Our second-best analysis also shows the positive role of an ethanol subsidy in the presence of a fuel tax, even when the net subsidy to ethanol with such a second-best optimal policy might be ambiguous.

An important contribution of our analysis is to show that ethanol mandates are equivalent to a policy of taxing fuel and subsidizing ethanol (i.e., providing tax credits to ethanol blenders). Specifically, a binding ethanol mandate is fully equivalent to a combination of a fuel tax and an ethanol subsidy that is revenue neutral. 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. Perhaps more important, when there are political constraints that limit the extent to which fuel taxes can be used, it is of interest to know which policy—ethanol subsidy or ethanol mandates—are preferable in such a (restricted) second-best setting. Exploiting the insight of our result that a binding mandate is fully equivalent to a revenue-neutral combination of an ethanol subsidy with a fuel tax, we have derived a novel welfare ranking of the two instruments (biofuels subsidy or mandate) in isolation. Specifically, we show that the use of a production/consumption mandate for ethanol actually leads to higher welfare than the use of an ethanol subsidy policy.

The fact that 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 in our setting is perhaps of more general interest. The reason for this non-equivalence 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 article, 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 Corporate Average Fuel Economy (CAFE) 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.

There is broad scope for applying and extending the analysis presented in this article. Because of the careful representation that our model provides for evaluating US ethanol policy, a useful application consists of calibrating and simulating the model to provide a quantitative assessment of the welfare impacts of alternative policy scenarios. An effort in this direction is provided by Cui et al. [4]. As for possible extensions, 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 Section 1 or the change in foreign greenhouse gas emissions that arises due to domestic policy, clearly impacts domestic welfare. Moreover, there are significant dynamic issues that arise in this context and that we have not addressed explicitly in the current 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 article. Such issues are the object of ongoing research projects of many researchers and will no doubt continue to provide challenges for environmental and resource economists for years to come.

Appendix A1. Proof of Proposition 5

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 $[tx_f(t,b)-bx_e(t,b)]\leq T_0$, using the instruments (b,t):

$$\max_{b,t}\; W(x_g(b,t),x_e(b,t)) \quad \text{s.t.} \quad tx_f-bx_e\leq T_0$$

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

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

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

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

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

$$L_\tau=(T_0+bx_e-tx_g)\geq 0,\quad \tau L_\tau=0,\quad \tau\geq 0$$

where $\eta\in(0,-1)$ was defined in (34) and $\delta\equiv(\partial x_e/\partial t)/(\partial x_g/\partial t)=(r_2/r_3)>0$. 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 $L(t^c(T_0),b^c(T_0),x_g^c(T_0),x_e^c(T_0),\tau^c(T_0))=W(x_g^c(T_0),x_e^c(T_0))\equiv\hat{W}(T_0)$.

Let (b^*,t^*,x_g^*,x_e^*) 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 (b^*,t^*) applies. Call the welfare level for this case $W^*=\hat{W}(T^*)\ \forall T_0\geq T^*$.

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, $\{x_g^c(T_0),x_e^c(T_0)\}|_{T_0=0}=\{x_g^m,x_e^m\}$ (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 $T^*\neq0$.

Next, let $T_s\equiv-b^sx_e^s<0$ 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., $\hat{W}(T_s)<\hat{W}(0)<\hat{W}(T^*)$. Finally, note that $W(t=0,b^s)\leq\hat{W}(T_s)$, 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. □

References

[1] S.T. Anderson, The Demand for Ethanol as a Gasoline Substitute, Working Paper, Michigan State University and NBER, July 25, 2011, doi:10.1016/j.jeem.2011.08.002, in press.

[2] A.W. Ando, M. Khanna, F. Taheripour, Market and social welfare effects of the renewable fuel standard, in: M. Khanna, et al. (Eds.), Handbook of Bioenergy Economics and Policy, 2010 (Chapter 14).

[3] Council of Economic Advisers, Searching for Alternative Energy Solutions, the Economic Report of the President, February 2008 (Chapter 7).

[4] J. Cui, H. Lapan, G. Moschini, J. Cooper, Welfare impacts of alternative biofuel and energy policies, American Journal of Agricultural Economics 93 (5) (2011) 1235–1256, doi:10.1093/ajae/aar053.

[5] H. de Gorter, D.R. Just, The welfare economics of a biofuel tax credit and the interaction effects with price contingent farm subsidies, American Journal of Agricultural Economics 91 (2) (2009) 477–488.

[6] H. de Gorter, D.R. Just, The economics of a blend mandate for biofuels, American Journal of Agricultural Economics 91 (3) (2009) 738–750.

[7] H. de Gorter, D.R. Just, The social costs and benefits of biofuels: the intersection of environmental, energy and agricultural policy, Applied Economic Perspectives and Policy 32 (1) (2010) 4–32.

[8] V.R. Eidman, Economic parameters for corn ethanol and biodiesel production, Journal of Agricultural and Applied Economics 39 (2) (2007) 345–356.

[9] J. Fargione, J. Hill, D. Tilman, S. Polasky, P. Hawthorne, Land clearing and the biofuel carbon debt, Science 319 (2008) 1235–1237.

[10] A.E. Farrell, R.J. Plevin, B.T. Turner, A.D. Jones, M. O'Hare, D.M. Kammen, Ethanol can contribute to energy and environmental goals, Science 311 (5760) (2006) 506–508.

[11] C. Ford Runge, B. Senauer, How Biofuels Could Starve the Poor, Foreign Affairs, May–June 2007.

[12] L.H. Goulder, I.W.H. Parry, Instrument choice in environmental policy, Review of Environmental Economics and Policy 2 (2) (2008) 152–174.

[13] R. Hahn, C. Cecot, The benefits and costs of ethanol: an evaluation of the government's analysis, Journal of Regulatory Economics 35 (2009) 275–295.

[14] T.W. Hertel, W.E. Tyner, D.K. Birur, The global impacts of biofuel mandates, The Energy Journal 31 (1) (2010) 75–100.

[15] S.P. Holland, J.E. Hughes, C.R. Knittel, Greenhouse gas reductions under low carbon fuel standards? American Economic Journal—Economic Policy 1 (1) (2009) 106–146.

[16] M. Khanna, A.W. Ando, F. Taheripour, Welfare effects and unintended consequences of ethanol subsidies, Review of Agricultural Economics 30 (3) (2008) 411–421.

[17] H. Lapan, G. Moschini, Biofuel Policies and Welfare: Is the Stick of Mandates Better than the Carrot of Subsidies? Working Paper no. 09010, Iowa State University, Department of Economics, June 2009.

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

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

[20] I.W.H. Parry, K.A. Small, Does Britain or the United States have the right gasoline tax? American Economic Review 95 (4) (2005) 1276–1289.

[21] D. Rajagopal, D. Zilberman, Environmental, economic and policy aspects of biofuels, Foundations and Trends® in Microeconomics 4 (5) (2008) 353–468.

[22] RFA (Renewable Fuel Association), Building Bridges to a More Sustainable Future: 2011 Ethanol Industry Outlook, February 2011.

[23] A. Salvo, C. Huse, Consumer Choice Between Gasoline and Sugarcane Ethanol, Working Paper, Northwestern University (KSM), February 2011.

[24] R. Schnepf, B.D. Yacobucci, Renewable Fuel Standard (RFS): Overview and Issues, CRS Report for Congress, July 14, 2010.

[25] T.D. Searchinger, R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, T-H. Yu., et al., Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change, Science 319 (5867) (2008) 1238–1240.

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

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

[28] M. Wang, M. Wu, H. Huo, Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types, Environmental Research Letters 2 (2007) 1–13.