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Carbon abatement in the fuel market with biofuels: Implications for second best policies ☆

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ABSTRACT

A carbon tax on fuel would penalize carbon intensive fuels like gasoline and shift fuel consumption to less carbon intensive alternatives like biofuels. Since biofuel production competes for land with agricultural production, a carbon tax could increase land rents and raise food prices. This paper analyzes the welfare effect of a carbon tax on fuel consisting of gasoline and biofuel in the presence of a labor tax, with and without a biofuel subsidy. The market impacts of a carbon tax are also compared with that of a subsidy. Findings show that if a carbon tax increases biofuel demand, the tax interaction effect due to higher fuel prices is exacerbated by higher land rent and food prices and greater erosion of the carbon tax base. Thus, the second best optimal carbon tax for fuel is lower with biofuel in the fuel mix, especially if biofuel is subsidized.

Introduction

Concerns about global warming and energy security have led to policies that aim to reduce greenhouse gas (GHG) emissions. The transport sector accounts for about 30% of total emissions in the United States (US), with 97% coming from fossil fuel combustion. Thus, reducing emissions from the transport sector is crucial to reducing overall emissions. Studies show that a tax on fuel is an effective instrument for reducing carbon emissions from gasoline use (Parry and Small, 2005; Sterner, 2007). Parry and Small (2005) derive the second best optimal fuel tax taking into account the presence of a distortionary labor tax. The analysis by Parry and Small (2005) assumes that gasoline is the only fuel. However, in recent years the use of biofuel as an alternative fuel source has grown rapidly. In 2012, the share of biofuel in US fuel supply was about 10%. To the extent that the carbon intensity of biofuel is lower than that of gasoline, the use of biofuel can expand the options for mitigating carbon emissions beyond reducing gasoline consumption and vehicle miles traveled.[1]

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[1] Unilateral carbon policies are likely to have leakage effects. In the case of biofuels, these can occur in the form of indirect land use changes (ILUC) induced by the increase in crop prices due to the diversion of crops from food to fuel production which lead to an expansion of cropland and a release of carbon stored in soils and vegetation. Estimates of the effect of ILUC on the GHG intensity of corn ethanol vary widely across studies and are sensitive to model assumptions, policy parameters, and biofuel volume (see Khanna and Crago, 2012). The ILUC related GHG intensity is a pecuniary externality (since it is driven by market-mediated effects) and hence should not be taxed from a social efficiency perspective (Zilberman et al., 2011). We therefore focus here on taxing biofuels based on their direct lifecycle GHG intensity, which causes a market failure.

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The presence of biofuel in the fuel mix is likely to affect the design and magnitude of the optimal fuel tax due to several reasons. First, since gasoline and biofuel have different emission intensities, a carbon-based tax would be more cost-effective for emissions reduction compared to a volumetric fuel tax. A carbon-based tax on fuels would tax both fuels in proportion to their GHG intensity and lead to the least-cost combination of fuel substitution and fuel reduction to reduce emissions.[2] Second, in the presence of biofuel, a carbon tax could also affect the agricultural sector since biofuel production is land intensive and competes with agricultural activities for land input. If the carbon tax increases biofuel consumption, agricultural land rent could also increase leading to higher food prices and income for landowners. In the presence of a labor tax, higher income and food prices add to the adverse welfare effect of a tax-induced increase in fuel prices. Finally, because biofuel is subsidized, increasing biofuel demand via a carbon based tax would increase the tax burden of the subsidy. Several countries including the US and those in the European Union have supported the production of biofuels by establishing mandates and providing subsidies (Sorda et al., 2010; Tyner, 2008). Since the share of biofuel in the fuel mix is likely to increase further, it is important to examine the impact of biofuel and biofuel policies on the optimal tax for fuel.

The use of taxes to internalize externalities dates back to Pigou (1932) and was later analyzed in the context of environmental externalities by Baumol and Oates (1971) and Baumol (1972). In a first best setting with perfect markets and no distortions other than a single externality, the optimal tax is the Pigouvian tax, which is equal to the marginal external damage (MED) of the externality. More recent literature focuses on analyzing the optimal tax in the presence of other pre-existing distortions such as a labor tax and shows that the level of the optimal environmental tax is influenced by its interaction with other existing market distortions (Goulder, 1995a; Bovenberg and Goulder, 1996; Bovenberg and de Mooij, 1994). In the context of this paper, the presence of a biofuel subsidy in addition to a labor tax affects the optimal carbon tax for fuel because a change in biofuel consumption also affects the level of distortionary labor taxes that are needed to finance the subsidy. When other distortions persist, the optimal tax may not be equal to the MED and the optimal policy is a “second best” policy because the true optimum cannot be attained. The literature suggests that in general, the second best optimal tax is lower than the MED because the welfare gains from using environmental tax revenues to reduce the labor tax are not sufficient to compensate for welfare losses from increased prices and reduction of the allocative efficiency of consumption (see Goulder (1995b) and Bovenberg (1999) for a comprehensive discussion). However, Parry (1995) shows that the second best optimal tax could be higher than the MED if the taxed commodity is a relatively weak substitute for leisure. In the case of a gasoline tax, Parry and Small (2005) find that the second best optimal tax for gasoline is above the Pigouvian tax since gasoline is a weak substitute for leisure.

In this paper, we derive the second best optimal carbon tax for fuel consisting of gasoline and biofuel in the presence of a labor tax, with and without a biofuel subsidy. We also compare the welfare effect of a biofuel subsidy with that of a carbon tax. We undertake this analysis by developing a framework in which consumers derive utility from leisure, miles, and food, and disutility from GHG emissions and miles-related externalities such as: congestion, air pollution and accidents. Miles are produced from fuel which consists of gasoline and biofuel. All produced goods use labor as an input, while land is only used as an input to the production of biofuel and food. The government obtains revenue by taxing labor, emissions and miles. The policy experiment considered is a revenue neutral increase in the carbon tax, with revenues from the carbon tax used to reduce the labor tax rate. We also consider a scenario with a fixed biofuel subsidy and analyze its implications for the optimal carbon tax. In addition, we examine the effect of a marginal increase in the subsidy rate, holding revenue fixed but allowing the labor tax to vary. We develop a numerical general equilibrium model to determine the magnitude of the second best optimal carbon tax, as well as the market and welfare impacts of the carbon tax and biofuel subsidy.

This paper contributes to the literature on optimal fuel taxation by considering the impact of biofuel and biofuel policies on second best fuel taxes. Our analysis extends the model developed by Parry and Small (2005) by including both food and fuel sectors, and land as a fixed factor. In addition, our numerical model incorporates the use of crude oil as a fixed factor in the production of gasoline. The presence of a fixed factor offsets the tax-induced increase in the price of gasoline by decreasing the marginal cost of gasoline production, and leads to an increase in the second best optimal tax (Bento and Jacobsen, 2007). We also examine the welfare effects of a biofuel subsidy while recognizing the need to finance it using distortionary labor taxes. Although previous studies (Khanna et al., 2008; Lasco and Khanna, 2009; De Gorter and Just, 2010) show that deadweight losses result from the current biofuel subsidy, none of these studies have examined the interaction of the subsidy with the labor tax, as we do in this paper.

We find that the second best optimal carbon tax is higher than the MED for carbon emissions. Similar to Parry and Small (2005), the implied fuel taxes for gasoline and biofuel are higher than the MED of each fuel. The presence of biofuel in the fuel mix lowers the value of the second best optimal carbon tax by 12.5% under our baseline assumptions, relative to the case with gasoline as the only fuel. With a biofuel subsidy, the second best tax is lower by 37.5%. The presence of biofuel leads to a larger reduction in the emissions tax base and a greater increase in land rent (which increases income and food prices) in response to an increase in the carbon tax. As a result of these two effects, the tax interaction effect is greater and the second best optimal carbon tax is lower compared to the case without biofuel. The reduction in the carbon tax due to biofuel ranges from 6.25% to 100%, depending on the elasticity of substitution between the two fuels, on the emissions intensity of biofuel relative to gasoline, on other parameters governing the responsiveness of labor supply and fuel demand to the tax, and on whether or not a biofuel subsidy exists.

[2] GHG intensity is measured in carbon dioxide equivalent emissions per unit of fuel.

We also find that a subsidy on biofuel decreases welfare by increasing the level of miles externalities and distortionary taxation to finance the subsidy. The second best carbon tax is lower with a subsidy because the subsidy leads to a greater reduction in the emissions tax base and a higher level of distortionary taxation. Sensitivity analysis shows that our qualitative findings are robust to a wide range of parameter assumptions.

Analytical framework

The representative consumer derives utility from leisure (L') and consumption of food (F) which is a clean good, and fuel (f) which is a dirty good used to produce miles (M).[3] Two types of fuel are available to consumers: a high-carbon fuel represented by gasoline (G) and a low carbon fuel represented by biofuel (B). The quantities of G and B are expressed in energy equivalent terms.[4] The function $f(G,B)$ is sufficiently general to allow for a broad range of technological substitution possibilities between G and B (see Holland et al. (2009) for a similar representation).[5]

Additionally, consumers derive disutilty from GHG emissions (E) from fuel consumption and miles-related externalities such as: congestion, air pollution, and traffic accidents. The level of emissions is $E=\delta^G G+\delta^B B$, with δ^G and δ^B denoting the GHG intensity of gasoline and biofuel, measured in carbon dioxide (CO_2) equivalents. The representative consumer's utility function is

$$U=u(L', C(M(f(G,B)),F))-\phi E-\psi M \tag{1}$$

where u is strictly concave. The marginal disutilities of GHG emissions and miles externalities are denoted by ϕ and ψ, respectively. The utility function exhibits weak separability between leisure (L') and consumption goods (C), and strong separability between consumption utility and the level of externalities.

The representative consumer derives income from labor (L) provided to firms. Labor supply is equal to a fixed time endowment ($\overline{L}$) minus leisure, $L=\overline{L}-L'$. The consumer also owns land (N) and derives income from land rent (R). The total amount of land is denoted by $\overline{N}$. Additionally, the consumer receives a transfer (Y) from the government. The tax rate on labor is denoted by T^L and the nominal wage (W) is set to unity and held constant. Thus total income, I is[6]

$$I=(1-T^L)L+RN+Y \tag{2}$$

The government taxes labor, fuel, and miles to obtain revenue. The tax on miles-related externalities is fixed and equal to the combined MED of congestion, air pollution, and traffic accidents. The carbon tax is levied on gasoline and biofuel such that the tax on each fuel is proportional to their GHG intensity, i.e., $T^i=T^C\delta^i$, $i=G,B$ and T^C is the carbon tax. The prices of gasoline, biofuel and food are denoted by P^G, P^B, and P^F respectively. Using Euler's theorem and the homogeneity property of the production functions for miles and fuel, the price per mile can be expressed as $P^M=(G/M)(P^G+T^G)+(B/M)(P^B+T^B)+T^M$. Thus, the consumer's budget constraint is

$$I-(P^G+T^G)G-(P^B+T^B)B-P^F F-T^M M=0 \tag{3}$$

Firms are owned by the representative consumer. Firms minimize cost and produce gasoline, biofuel, and food at zero profit. Gasoline is produced using labor, while biofuel and food are produced using labor and land. The production functions for goods are given by $G=G(L^G), B=B(L^B,N^B)$ and $F=F(L^F,N^F)$.[7]

Maximizing (1) subject to (3) yields optimal consumption levels. Substituting the optimal quantities of L', G, B, and F in the utility function yields the indirect utility function as a function of the carbon tax, income, level of externalities and the vector of prices (P). The effect of a marginal increase in T^C on V is given by the following equation (see Appendix A for derivation)[8]:

$$\frac{dV}{\lambda dT^C}=-\frac{\phi}{\lambda}\frac{dE}{dT^C}+T^C\frac{dE}{dT^C}+T^L\frac{dL}{dT^C} \tag{4}$$

The first term is the change in disutility caused by emissions.[9] The second and third terms reflect the change in the economy's tax base and the non-environmental welfare effect of a marginal increase in the carbon tax. A reduction in the economy's tax base indicates greater inefficiency in the tax system as a mechanism to generate revenue, as higher marginal

[3] The focus of this paper is on the effect of a carbon tax on fuel, thus we assume that GHG emissions from the food sector are zero. In practice proposed regulation to limit GHG emissions by setting a price on carbon have typically focused on energy intensive sectors, and excluded agricultural production (EIA, 2009).

[4] Biofuel such as ethanol has two-thirds the energy content of gasoline.

[5] The representative consumer's miles consumption implies a choice of fuel consisting of a blend of gasoline (G) and biofuel (B). Although gasoline and biofuel are perfect substitutes as fuels, demand and supply side constraints such as fleet structure and distribution facilities prevent them from being blended as such, leading to imperfect substitution between the two fuels in the short run. In the long run however, demand and supply side constraints could disappear, leading to perfect substitution of fuels.

[6] In the analytical model, we abstract from the government's ability to tax land rent income, although in the numerical simulation we consider the presence of a tax on land rent. If the government could tax all of rent income, then changes in land rent would not change the representative consumer's income.

[7] In the numerical simulation, we introduce capital as a production input for all goods and crude oil as a fixed input to gasoline production.

[8] Note that the tax also increases income through increased land rent revenue, but this effect is fully offset by the increase in expenditures on biofuel and food.

[9] λ is the marginal utility of income.

tax rates are needed to generate the same amount of revenue. Since a carbon tax would decrease emissions, the sign of the second term is negative. Thus, the sign and magnitude of the effect of the tax on labor supply (third term) determines whether the net effect of the tax on the economy's tax base is positive or negative.

An expression for the second best optimal carbon tax is obtained by setting Eq. (4) to zero[10]:

$$T^{C*} = \frac{\phi}{\lambda} - T^L \frac{(dL/dT^C)}{(dE/dT^C)} \tag{5}$$

The first term is the MED corresponding to emissions. The second term denotes the effect of the carbon tax on labor tax revenues, relative to the tax-induced reduction in emissions. The second term shows that the non-environmental benefit of the tax, i.e. its ability to increase the efficiency of the tax system, is positive if the carbon tax leads to an increase in labor supply. An increase in labor supply due to the tax implies that T^{C*} exceeds the MED of emissions, and its value is greater the more labor supply increases with the tax. Conversely, if labor supply decreases, T^{C*} is lower than the MED, and its value is smaller the more labor supply decreases with the tax.

The greater the reduction in emissions due to the tax (dE/dT^C), the smaller the magnitude of the second term in (5), implying that the more price elastic the taxed good is, the smaller the magnitude of the non-environmental component of the tax in relation to the MED. Thus, the second best optimal carbon tax is more likely to be higher than the MED if it is levied on a good that has a lower price elasticity because the tax will lead to a smaller reduction in the demand for the taxed good.

The following section discusses the effect of the tax on emissions and labor supply, and how the presence of biofuel affects dE/dT^C and dL/dT^C.

Effect of the tax on emissions

The effect of the tax on the level of emissions depends on how the tax affects demand for gasoline and biofuel. Using the definition of E, the change in emissions with respect to the tax is given by

$$\frac{dE}{dT^C} = \delta^G \frac{dG}{dT^C} + \delta^B \frac{dB}{dT^C} \tag{6}$$

Assuming gasoline and biofuel are perfect substitutes (see Anderson (2012) for a similar representation), (6) can be expressed as (see Appendix B for derivation)

$$\frac{dE}{dT^C} = \frac{\varepsilon^{MP}}{M_G}\frac{M}{P^M}\delta^{G2} - \left(\varepsilon^{FP}\frac{F}{P^F}(\delta^B - \delta^G)\right)(\delta^G - \delta^B) \tag{7}$$

where ε^{MP} is the price elasticity of miles demand, ε^{FP} is the price elasticity of food demand, and M_G is the marginal product of gasoline in miles production. The first term in (7) represents the effect of reduced miles demand as the carbon tax increases the price of miles. Without biofuel, only the first term would affect emissions. With biofuel, the second term in (7) is negative if the GHG intensity of biofuel is lower than that of gasoline $(\delta^B - \delta^G < 0)$ and food is a normal good such that its price elasticity is negative $(\varepsilon^{FP} < 0)$. Thus, a marginal change in the carbon tax decreases emissions more in the presence of biofuel than otherwise. The greater the price elasticity of miles demand, and the difference between the emissions intensities of gasoline and biofuel, the greater the reduction in emissions with respect to a change in the carbon tax. In addition, a more price elastic demand for food also increases emissions reduction. Since biofuel and food compete for land input, a more elastic demand for food results in a greater reduction in food production as land rent increases, freeing up more land for biofuel production and increasing emissions reduction.

While greater emissions reduction increases the environmental benefit of the carbon tax (first term in (4)), it also leads to a greater reduction in the tax base (second term in (4)). Eq. (5) shows that if labor supply increases with the tax, a larger reduction in emissions leads to a smaller magnitude of the non-environmental (tax efficiency) benefit of the carbon tax, resulting in a lower second best optimal tax.

Effect of the tax on labor supply

Labor supply is a function of the exogenous variables in the indirect utility function. Noting that income depends on T^L and R, and that prices of land-using goods depend on R, the change in labor supply for a marginal change in T^C can be expressed as

$$\frac{dL}{dT^C} = \frac{\partial L}{\partial T^L}\frac{dT^L}{dT^C} + \frac{\partial L}{\partial T^C} + \left(\frac{\partial L}{\partial R} + \frac{\partial L}{\partial P}\frac{dP}{dR}\right)\frac{dR}{dT^C} \tag{8}$$

The first term is the revenue recycling effect that shows the effect of the carbon tax on labor supply due to a change in the labor tax rate. The use of revenue from the carbon tax to reduce the tax rate on labor has a positive effect on labor

[10] This tax is necessarily second best because other distortions exist in the economy. The first best tax rate is equal to the MED, with no other distortions present. Note also that T^{C*} corresponds to a second best optimal labor tax rate, since both are jointly determined.

supply. The second term is the tax interaction effect which is the partial derivative of labor supply with respect to the carbon tax. The tax on carbon increases the price of taxed goods, inducing a substitution away from consumption goods to leisure, and decreasing labor supply. These two effects normally constitute the labor market impact of an environmental tax. With biofuel, the carbon tax also affects labor supply through its effect on land rent (third term). An increase in land rent increases food prices and income. If leisure is a normal good, additional income and higher prices reduce labor supply (all else equal). Thus, if the tax increases biofuel demand, land rent increases and the third term in (8) has a negative impact on labor supply.

Numerical simulation

In order to quantify the impact of biofuels on the second best optimal carbon tax for fuels, we develop a numerically solved general equilibrium model of the US economy. This model is used to obtain estimates of T^{C*} under different policy scenarios and different assumptions about the composition of fuel.[11] The numerical model also allows us to examine the changes in prices and quantities of goods and factor inputs in the model in response to a change in the carbon tax.

The structure of the numerical model follows the analytical framework presented in the previous section. However, we relax some of the assumptions in the analytical model. Capital (K) is added as a factor of production. The rental rate for capital is denoted by Z, and the total available capital is $\overline{K}$. Crude oil is also introduced as an input to gasoline production. A portion of crude oil input is assumed to be imported, and imported crude oil (CO) is assumed to be a fixed input to gasoline production. As demand for gasoline decreases, domestic extraction and refining of crude oil decreases while the quantity of imported crude oil remains constant. The prices of labor and capital are fixed, while prices of land and imported crude oil are endogenously determined. We also relax the assumption that the government cannot tax land rent. Finally, an additional consumption good (O) for all other goods is included to model the size of the fuel and food sectors relative to the level of total consumption in the US economy.

Utility follows a nested constant elasticity of substitution (CES) functional form given by

$$U=(\alpha_{UL'}L'^{((\sigma_U-1)/\sigma_U)}+\alpha_{UC}C^{((\sigma_U-1)/\sigma_U)})^{(\sigma_U/(\sigma_U-1))}-\ \omega(G+B) \tag{9}$$

$$C=(\alpha_{CM}((\alpha_{MG}G^{((\sigma_M-1)/\sigma_M)}+\alpha_{MB}B^{((\sigma_M-1)/\sigma_M)})^{(\sigma_M/(\sigma_M-1))})^{((\sigma_C-1)/\sigma_C)}+\alpha_{CF}F^{((\sigma_C-1)/\sigma_C)}+\alpha_{CO}O^{((\sigma_C-1)/\sigma_C)})^{(\sigma_C/(\sigma_C-1))} \tag{10}$$

The elasticity of substitution between leisure and consumption is given by σ_U while the elasticities of substitution among consumption goods and between gasoline and biofuel are given by σ_C and σ_M. The α parameters in (9) and (10) denote expenditure shares. The term $\omega(*)$ is the disutility associated with fuel externalities from emissions and mile-related externalities.

The consumer purchases consumption goods and obtains revenue by supplying factor inputs to firms. The government also provides a fixed amount of transfer to the consumer which is financed by taxes on labor, fuel and land rent. The total tax on fuel consists of a tax on emissions and a tax on miles-related externalities. The tax on miles is levied on fuel according to the MED of miles-related externalities per unit of fuel consumed.

The government budget constraint is given by

$$Y=T^LWL+T^NRN+(T^{G'})P^GG+(T^{B'})P^BB \tag{11}$$

with T^N denoting the tax on land rent and $T^{G'}$ and $T^{B'}$ denoting tax rates for gasoline and biofuel including taxes on both emissions and miles. We also consider a case in which the government's provides a subsidy to biofuel consumption. With the subsidy, the term SP^BB is subtracted from the government budget constraint, where S is the subsidy rate for biofuel.

Firms maximize profits from the production of goods. The production functions for gasoline, biofuel, food, and other goods have the following functional forms:

$$G=(\alpha_{GCO}CO_G^{((\sigma_G-1)/\sigma_G)}+\alpha_{GL}L_G^{((\sigma_G-1)/\sigma_G)}+\alpha_{GK}K_G^{((\sigma_G-1)/\sigma_G)})^{(\sigma_G/(\sigma_G-1))} \tag{12}$$

$$B=(\alpha_{BL}L_B^{((\sigma_B-1)/\sigma_B)}+\alpha_{BN}N_B^{((\sigma_B-1)/\sigma_B)}+\alpha_{BK}K_B^{((\sigma_B-1)/\sigma_B)})^{(\sigma_B/(\sigma_B-1))} \tag{13}$$

$$F=(\alpha_{FL}L_F^{((\sigma_F-1)/\sigma_F)}+\alpha_{FN}N_F^{((\sigma_F-1)/\sigma_F)}+\alpha_{FK}K_F^{((\sigma_F-1)/\sigma_F)})^{(\sigma_F/(\sigma_F-1))} \tag{14}$$

$$O=(\alpha_{OL}L_O^{((\sigma_O-1)/\sigma_O)}+\alpha_{ON}N_O^{((\sigma_O-1)/\sigma_O)}+\alpha_{OK}K_O^{((\sigma_O-1)/\sigma_O)})^{(\sigma_O/(\sigma_O-1))} \tag{15}$$

The α parameters in (12)–(15) represent expenditure shares of production inputs. The σ terms are elasticities of substitution among production inputs. Equilibrium requires market clearing in goods and factor markets.

Data and calibration

The level of consumption and availability of factor inputs are based on the US economy in 2004. Data are obtained from a social accounting matrix constructed using data from the Global Trade Analysis Project (Lasco, 2009). As shown in Eq. (10), consumption is disaggregated into fuel (gasoline and biofuel), food, and other goods. The value of food expenditures is

[11] The model is solved using the MPSGE compiler in GAMS. See Rutherford (1998) and Markusen (2002) for a discussion of MPSGE models.

Table 1
Parameter values.

Scenario	Baseline	Low	High
Elasticity of substitution			
Leisure and consumption (σ_U)	1	0.1	2
Consumption goods (σ_C)	0.1	0.05	1
Biofuel and gasoline (σ_M)	5	1	10
Factors of production ($\sigma_G, \sigma_B, \sigma_F, \sigma_O$)	0.5	0.1	1
Emission reduction from biofuel relative to energy equivalent gasoline (%)	40	20	60
MED of CO_2 (\$ per ton CO_2)	25	5	65

derived from the share of food expenditures in total consumption, which is 10% based on data from the Bureau of Labor Statistics (BLS, 2010) and the US Department of Agriculture (USDA, 2000). Fuel expenditures, as well as the share of biofuel and gasoline in total fuel supply is based on consumption and prices in 2009. Prices and quantities of gasoline and biofuel (ethanol) are obtained from the Nebraska Ethanol Board and are normalized to 2004 prices (NEB, 2009).

The α parameters in Eqs. (9)–(15) are calibrated based on expenditure shares in the social accounting matrix. The shares of leisure and consumption in utility, and the expenditures shares of consumption goods and production inputs are given in Appendix C. The data indicate that fuel expenditures are 3% of total consumption expenditures and biofuel expenditures account for 8% of fuel expenditures. Based on EIA data on the share of crude oil expenditures in gasoline production and on the share of imports in crude oil supply in 2009, we assume that imported crude oil accounts for 60% of input expenditures for gasoline production in the US (Cohen, 2011; EIA, 2011, 2012). The share of land, labor, and capital inputs in biofuel production are derived from detailed estimates of production costs of corn ethanol (Crago et al., 2010).

The elasticity of substitution between leisure and consumption (σ_U) is calibrated to be consistent with the value of labor supply relative to total economic output as well as estimates of compensated and uncompensated labor supply elasticities (see Fox, 2002). Based on a compensated labor supply elasticity of 0.2 and an uncompensated labor supply elasticity of 0.33 (Parry and Small, 2005; Blundell and MacCurdy, 1999; Fuchs et al., 1998), the elasticity of substitution between leisure and consumption is assumed to be 1. We test for sensitivity to lower and higher values of the elasticity of substitution between leisure and consumption (see Table 1). Based on Parry (2001) and Bento and Jacobsen (2007), the tax rate on labor is set to 0.4. Following Bento and Jacobsen (2007), we use a land tax rate of 0.1. For the subsidy on biofuel, we assume a subsidy rate of 0.2 based on the ratio of government expenditures to finance the volumetric excise tax credit for corn ethanol in 2009 and the value of biofuel production in the same year (Yacobucci, 2012; NEB, 2009).

For the elasticity of substitution among consumption goods (σ_C) we use a central value of 0.1 to be consistent with empirical estimates that show inelastic demands of fuel and food (ERS, 2003; Greene and Ahmad, 2005). For the elasticity of substitution between biofuel and gasoline (σ_M) we use a central value of 5, and test for sensitivity of results to higher and lower values. A summary of baseline and alternative values for elasticities of substitution are given in Table 1.

Externality cost and GHG intensity of fuels

External costs of fuel consumption ($\omega(*)$) come from miles related externalities and GHG emissions. Miles related externalities include congestion, air pollution and traffic accidents. Based on the estimate by Parry and Small (2005), we assume that the marginal external damage associated with miles externalities is \$0.77 per gallon.

To derive the MED of fuel associated with GHG emissions, the GHG intensity of each fuel is multiplied by the MED of emissions. We assume a MED of \$25 per ton of carbon dioxide (CO_2) equivalent emissions based on estimates of the social cost of carbon for use in US regulatory analysis. For 2010, estimates from the Interagency Working Group range from \$5 to \$65 per ton of CO_2 emissions with a central value of \$21 in 2007 dollars (Greenstone et al., 2010, 2011). In addition, the proposed American Clean Energy Security Act (ACES) would have established a cap-and-trade program for GHG emissions. In the base case analyzed by the EIA (2009), the carbon prices expected to prevail with the implementation of the ACES Act range from \$20 per metric ton of CO_2 in 2010 to \$65 per metric ton of CO_2 in 2030 and onwards. We test for sensitivity of our results to a low value of \$5 per metric ton of CO_2 emissions and a high value of \$65 per metric ton of CO_2 emissions.

The GHG intensities of gasoline and biofuel are calculated from Life Cycle Assessment (LCA) studies that measure emissions from "well-to-wheel", or from the production of inputs that go into fuel production to emissions from the combustion of the fuel. For gasoline, emissions include those from crude oil recovery, transport and refining, distribution to the pump, and end of pipe emissions. For biofuel, emissions include those from feedstock farming, biofuel production in the refinery, distribution, and end of pipe emissions. GHG emissions from gasoline are fairly well established. We use a GHG intensity of 12.05 kg CO_2 per gallon of gasoline based on estimates by CARB (2009). The assumed MED of a ton of CO_2 and the GHG intensity of gasoline imply that the MED of emissions from gasoline is \$0.3 per gallon.[12]

[12] Parry and Small (2005) consider only tailpipe emissions and use the carbon content of those emissions (2.4 kg carbon per gallon gasoline) to calculate the carbon intensity of gasoline, instead of using life-cycle CO_2 emissions. For the MED of emissions, they use \$25 per ton carbon (not CO_2). Thus, their calculated MED of gasoline emissions is \$0.06 per gallon.

In the case of biofuel, LCA emissions are less certain. Emissions depend on the type of feedstock used, farming practices and the technology used for refining. Early studies showed that corn ethanol emits 12–20% less emissions than energy equivalent gasoline (Farrell et al., 2006; Wang et al., 2007). Recent studies with more technologically advanced refineries estimate that emissions from corn ethanol are over 40% lower compared to gasoline (Liska et al., 2009). Ethanol produced from biomass has even greater potential to reduce emissions with some estimates at over 90% lower compared to gasoline (Adler et al., 2007; Khanna and Crago, 2012). We use a GHG intensity of 4.7 kg CO_2 per gallon of biofuel, which implies a 40% reduction in emissions compared to an energy equivalent unit of gasoline and a MED of $0.18 per gasoline energy equivalent gallon of biofuel. In the sensitivity analysis we consider lower (20%) and higher (60%) levels of emissions reduction from biofuel.

Results

Second best optimal carbon tax

Numerical results confirm our hypothesis that the second best optimal carbon tax is lower with biofuel in the fuel mix, especially when biofuel is subsidized. Values for the second best optimal carbon tax for fuel with and without biofuel are given in Table 2, under alternative assumptions about the elasticity of substitution between biofuel and gasoline. With gasoline as the only fuel, the second best tax is $100 per ton of CO_2. The large second best tax relative to the MED of carbon ($25) is due to the very low elasticity of substitution among consumption goods and fairly high elasticity of substitution between leisure and consumption assumed in the baseline. As shown in the sensitivity analysis below (Table 6), with greater elasticity among consumption goods and low elasticity of substitution between leisure and consumption goods, the magnitude of the second best tax is close to the MED of carbon because there is a larger reduction in the quantity of fuel and emissions.

With the inclusion of biofuel, under baseline assumptions, the second best tax is $87.5 per ton CO_2, or 12.5% lower than in the case with gasoline only. In the presence of biofuel, a marginal change in the carbon tax leads to higher land rent and food prices which reduce labor supply, and greater emissions reduction which leads to a larger decrease in the carbon tax base. Greater emission reduction and a reduction in labor supply both make taxation more inefficient and reduce the magnitude of the second best carbon tax relative to the MED of carbon emissions (see Eq. (5)). Biofuel may also increase the second best optimal carbon tax by reducing gasoline demand, which could then decrease gasoline prices and increase labor supply. However, our results show that the negative welfare effects of increasing land rent, food prices and emissions reduction offset the positive welfare effect of reducing gasoline prices. The second best carbon tax decreases with a higher elasticity of substitution between gasoline and biofuel because of the larger tax-induced shift towards biofuel.

Table 2
Second best optimal carbon tax ($/ton CO_2).

	Gas only	Gas and biofuel		
Elasticity of substitution between fuels	N/A	1	5	10
Tax	100	97.5	87.5	85
Tax and biofuel subsidy	–	90	62.5	55

Table 3
Market and externality effects of alternative policies (% Change).

	Carbon tax			Cabon tax and subsidy	Subsidy only
Elasticity of substitution between fuels	Gas only	5	10	5	5
Quantity emissions	−1.59	−1.85	−1.98	−1.95	−0.47
Quantity total fuel	−1.59	−1.20	−1.11	−0.84	1.35
Quantity gasoline	−1.59	−2.85	−3.32	−3.71	−2.80
Quantity biofuel	–	16.33	21.64	22.79	43.45
Quantity labor	0.43	0.38	0.37	0.31	0.01
Price gasoline	21.45	17.30	15.83	15.23	−7.85
Price biofuel	–	13.15	17.95	9.76	−0.15
Price food	0.01	0.02	0.03	0.03	0.04
Land rent	0.68	2.04	2.56	3.33	3.70
Labor tax rate	−7.90	−6.75	−6.44	−5.28	0.49

Note: Numbers in columns 2–5 are % changes for an increase in the carbon tax from $25 per ton CO_2 to $50 per ton CO_2.

The results in Table 3 further illustrate the effect of biofuel and biofuel policies on land rent, food prices, and emissions. The effect of increasing the carbon tax from the Pigouvian level of \$25 per ton CO_2 to \$50 per ton CO_2 is shown in columns 2–5. Revenue from increasing the carbon tax is used to reduce the labor tax in a revenue neutral manner so that government transfers remain constant.

With gasoline as the only fuel, a doubling of the carbon tax increases the price of gasoline and reduces gasoline demand and emissions by 1.6%. The reduction in demand for gasoline frees up labor and capital for use in other production activities and decreases their prices relative to that of land. Since the nominal wage and the capital rental rate are assumed to be constant, this shift in the use of capital and labor to land-using sectors increases the marginal productivity of land and thus land rent by 0.68%. The increase in land rent leads to a 0.01% increase in the price of food. The impact of land rent on food price is small because land input accounts for less than 1% of the cost of food production. Higher land rent and gasoline price decrease labor supply. On the other hand, reductions in the labor tax rate financed by carbon tax revenues increase labor supply. The net effect of the carbon-labor tax swap is to increase labor supply by 0.43% and decrease the labor tax rate by 7.9%.

The presence of biofuel increases the potential for gasoline consumption to decrease with a carbon tax due to the availability of a less carbon intensive substitute. With biofuel in the fuel mix, gasoline consumption decreases by 2.8% while biofuel consumption (on an energy equivalent basis) increases by 16.3%. The reduction in emissions is 1.8% which is 16% greater than that under the gas only case. The increase in biofuel production increases competition for land and increases land rent by 2.0%, a three-fold increase compared to the gas-only case. As a result, the increase in the price of food doubles to 0.02%, compared to the gas-only case. Higher land rent and food price leads to a smaller increase in labor supply (0.38%). The larger reduction in the tax base for carbon and the smaller increase in labor supply lead to a smaller change in the labor tax rate (− 6.8%), which is 14% lower compared to the case with only gasoline.

The inclusion of biofuel in the fuel mix also affects the change in total consumption of fuel and miles in response to a change in the carbon tax. With only gasoline in the fuel mix, the percent reduction in overall fuel consumption is equal to the reduction in gasoline. However, with biofuel, the reduction in fuel consumption is smaller (− 1.2%) compared to the case with only gasoline. Although gasoline demand falls more with biofuel, the increase in biofuel demand offsets the reduction in gasoline demand and leads to a higher level of fuel consumption, relative to the case with only gasoline.

A greater elasticity of substitution between gasoline and biofuel decreases the cost of switching to biofuels, further incentivizing the consumption of biofuel instead of gasoline in response to an increase in the carbon tax. Under the assumption of more elastic substitution between fuels, gasoline consumption decreases by 3.3% while biofuel consumption increases by 21.6%. As shown in the fourth column of Table 3, this leads to emissions reduction of 1.9%, which is 24% greater than the gas-only case. The higher level of biofuel consumption leads to a greater increase (2.6%) in land rent. The price of food increases by 0.03%, which is three times the increase in the gas-only case and 50% higher compared to the baseline case with biofuel. Thus, the labor tax rate decreases by 6.4% which is 18% lower than in the case with only gasoline.

Second best optimal carbon tax with pre-existing subsidy

Currently, instead of incentivizing biofuel through a carbon tax, a biofuel subsidy is in place.[13] As shown in Table 2, with a pre-existing subsidy rate of 0.2 for biofuel, the second best optimal carbon tax is \$62.5 per ton of CO_2. A pre-existing subsidy on biofuel reduces the second best carbon tax by increasing the magnitude of the tax interaction effect in two ways: first, it increases the tax burden of increasing biofuel consumption because each additional unit of biofuel consumption increases government expenditure to finance the subsidy. Second, the carbon tax combined with a subsidy on biofuel further incentivizes biofuel consumption, leading to greater reduction in emissions and higher land rent and food prices. Table 3 column 5 shows the effect of increasing the carbon tax from \$25 to \$50 per ton CO_2 in the presence of a biofuel subsidy. Compared to the case with no subsidy (Table 3, column 3), the reduction in emissions (− 1.9%) is 5.4% larger and the increase in land rent (3.3%) is 63% greater with the subsidy. Both of these effects lead to a smaller reduction in the labor tax rate (− 5.3%) and a lower second best carbon tax.

Biofuel subsidy

We also examine the effect of a subsidy by itself with no carbon tax. Increasing the subsidy rate from zero to 0.2 decreases gasoline demand by 2.8% and increases biofuel demand by 43.4% (Table 3 column 6). A biofuel subsidy could increase or decrease emissions depending on the elasticity of substitution between gasoline and biofuel and their relative emissions intensities (see Khanna et al., 2008). Given our baseline assumptions, the subsidy leads to a small reduction (− 0.47%) in emissions.

Unlike a carbon tax, a subsidy decreases the price of fuels. The price of biofuel is directly reduced by the subsidy, although this reduction is partially offset by the increase in the marginal cost of biofuel, as increasing biofuel production drives up land rent. The price of gasoline decreases due to the reduction in its marginal cost as decreased demand for gasoline reduces the price of the fixed crude oil input. The reduction in the price of fuel increases real wage and labor supply. On the other hand, higher land rent due to increased biofuel demand increases food price and income, decreasing labor supply. The net effect is a marginal (0.01%) increase in labor supply. Although the labor tax base expands, the reduction in

[13] From 1978 to 2011, corn ethanol received subsidies of \$0.3–\$0.6 per gallon. There is currently a subsidy of \$1.01 per gallon for cellulosic ethanol.

the carbon tax base and the additional revenue requirement of the subsidy lead to a 0.49% increase in the labor tax rate. Because the subsidy decreases the price of fuels, overall fuel consumption increases, leading to an increase in miles related externalities.

Fuel taxes

Table 4 shows per gallon fuel taxes on gasoline and biofuel. Per gallon fuel taxes are obtained by multipying T^{C*} with the respective GHG intensity of each fuel, and adding the per gallon tax on miles-related externalities ($0.77). With only gasoline in the fuel mix, the second best optimal fuel tax is $1.97 per gallon, which is 82% higher than the combined MED of miles and emissions externalities of $1.07. With biofuel in the fuel mix, the per gallon gasoline tax is $1.85 without a biofuel subsidy and $1.52 with a biofuel subsidy, which is a reduction of 6% and 23% respectively, compared to the case with only gasoline. Biofuel taxes range from $1.21 to $1.38 per gasoline energy equivalent gallon (or $0.8–$0.92 per gallon by volume) depending on whether or not a biofuel subsidy exists. The per gallon fuel tax on biofuel is lower compared to gasoline because its GHG intensity is lower.

Welfare effects

Table 5 shows the welfare effect of imposing the second best optimal carbon tax, relative to the case where the carbon tax is set equal to the carbon MED of $25 per ton CO_2. With gasoline as the only fuel, increasing the carbon tax from $25 per ton to the second best optimal tax of $100 per ton leads to a welfare gain of $18.9 billion dollars. Forty-six percent of the net welfare gain is due to increased social surplus, as the efficiency of the tax system improves with the carbon-labor tax swap, while 54% is due to increased welfare from a lower level of externalities.

With biofuel, the net gain from increasing the carbon tax to its second best optimal level is lower by 32% at $12.9 billion. Higher land rent and food prices due to increased biofuel demand leads to a smaller increase in labor supply, thus reducing the efficiency gain from the carbon-labor tax swap (see last term in Eq. (4)). Although the reduction in emissions is greater with biofuel, the reduction in fuel use is smaller, leading to a smaller reduction in miles related externalities. Thus, the welfare gain from the reduction in externalities is smaller with biofuel compared to the gas-only case. Imposing the second best optimal carbon tax when a subsidy is in place increases welfare, although the net welfare gain ($3.9 billion) from increasing the tax from its Pigouvian level to its second best optimal level is 70% smaller compared to the case without a subsidy.

Table 4
Second best optimal fuel taxes ($/gallon).

	Gas only	Gas and biofuel	
Fuel	Gas	Gas	Biofuel
Tax	1.97	1.82	1.38
Tax and subsidy	–	1.52	1.21

Note: The fuel tax in the gas only case corresponds to a second best optimal carbon tax of $100/ton CO_2. With gasoline and biofuel, the carbon tax corresponds to the case with a second best optimal carbon tax of $87.5/ton CO_2. Fuel tax for biofuel is for an energy equivalent volume.

Table 5
Welfare effects of second best policies (billion dollars, in 2004 prices).

	Gas only	Gasoline and biofuel		
Policy		Tax	Tax and subsidy	Subsidy only
Second best carbon tax ($ per ton CO_2)	100	87.5	62.5	N/A
Social surplus	8.69 (0.07)	6.92 (0.06)	1.36 (0.01)	−0.54 (−0.005)
Externalities	10.27 (−6.61)	5.98 (−3.87)	2.63 (−1.71)	−0.59 (0.64)
Net welfare	18.96 (0.16)	12.9 (0.11)	3.99 (0.03)	−1.13 (−0.01)

Note: Numbers in parentheses in columns 2–4 are percentage changes relative to the baseline case with a carbon tax equal to the MED of CO_2 ($25/ton CO_2).

In contrast to the scenario with taxes, the welfare effect of increasing the biofuel subsidy rate from 0 to 0.2 is negative at −$1.1 billion due to the additional distortionary tax burden of financing the subsidy, and increased level of externalities. Although emissions decrease by 47%, total fuel use increases by 1%, leading to an increase in miles-related externalities. The cost of increased miles-related externalities offsets the welfare gain from reduced emissions, leading to a higher level of externalities.

Sensitivity

The effect of different assumptions about the elasticity of substitution among the different production inputs and consumption goods, and between leisure and consumption is presented in Table 6.

The elasticity of substitution between leisure and consumption (σ_U) determines the extent to which the share of leisure and consumption changes in response to a change in their relative prices. An increase in the carbon tax increases the composite price of consumption goods, increasing leisure demand and decreasing labor supply. On the other hand, if revenues from the carbon tax are used to lower the labor tax rate, the price of leisure increases, thus decreasing leisure demand and increasing labor supply. Our numerical simulations show that leisure responds more to a change in the wage rate, rather than to a change in the price of consumption goods (i.e. the revenue recycling effect is greater than the tax interaction effect). A higher value of the elasticity of substitution between leisure and consumption goods allows for a larger reduction in leisure demand (and increase in labor supply) in response to a lower labor tax rate. Thus a higher value of σ_U leads to a stronger revenue recycling effect, and a higher value of the second best tax, as shown in Table 6.

The elasticity of substitution among consumption goods (σ_C) determines the response of quantity demanded of goods to changes in relative prices of those goods. An increase in the carbon tax increases the price of fuel, and decreases demand for fuel and miles. A higher value of σ_C leads to a greater reduction in demand for fuel and a greater reduction in the carbon tax base, leading to a second best tax that is 45% lower compared to the baseline case. Conversely, setting σ_C to a lower value of 0.05 increases the second best carbon tax relative to the baseline. The impact of biofuels on the carbon tax is smaller with a higher value of σ_C because the change in biofuel demand is smaller due to the consumption of less fuel and more of other goods.

The elasticity of substitution among production inputs (land, labor, capital, and crude oil) affects the extent to which inputs can be substituted for each other in response to changes in factor prices. With a smaller elasticity of substitution among production inputs, there is a smaller reduction in fuel demand (and emissions), thus the second best tax is larger. The opposite occurs if the elasticity of substitution between production inputs is higher: there is greater reduction in fuel consumption and emissions, and the second best optimal carbon tax is lower.

If the energy equivalent emissions intensity of biofuel is 60% instead of 40% lower compared to gasoline, the carbon tax would create stronger incentives to increase the consumption of biofuel instead of gasoline. Gasoline consumption decreases more compared to the base case, and overall emissions reduction is also larger. The higher level of biofuel consumption leads to a greater increase in land rent and food prices, which in turn leads to a stronger tax interaction effect. Thus, the second best optimal carbon tax is 11% lower than in the base case. If the emissions intensity of biofuel is 20% lower than that of gasoline, the second best tax is 11% higher than the base case.

Table 6
Sensitivity analysis: second best optimal carbon tax ($/ton CO_2).

	Gas only	Gas and biofuel	
Policy	Carbon tax	Carbon tax	Carbon tax and subsidy
Baseline	**100**	**87.5**	**62.5**
Elasticity of substitution between leisure and consumption goods (σ_U)			
Low	40	37.5	0
High	112.5	102.5	80
Elasticity of substitution among consumption goods (σ_C)			
Low	112.5	92.5	62.5
High	55	52.5	57.5
Elasticity of substitution among production inputs ($\sigma_G, \sigma_B, \sigma_F, \sigma_O$)			
Low	110	102.5	87.5
High	97.5	80	50
Reduction in emissions intensity of biofuel relative to energy equivalent gasoline			
Low	–	97.5	75
High	–	77.5	52.5
Marginal external damage of CO_2 ($ per ton CO_2)			
Low	97.5	85	57.5
High	102.5	92.5	67.5

The assumed MED of carbon determines the welfare gain from a reduction in GHG emissions. A lower MED of carbon decreases welfare gain from reducing externalities related to emissions as the carbon tax is increased, and leads to a lower value of the second best optimal tax (see Appendix Eq. (A.1)). Conversely, a higher MED of carbon increases welfare gain from reducing emissions, and makes it optimal to reduce emissions further by increasing the carbon tax. For smaller values of the MED of carbon, changes in the externality cost of emissions is a smaller component of welfare compared to changes in the cost of externalities related to miles consumption and to changes in the tax-efficiency that result from increasing the carbon tax and using revenues to decrease the labor tax rate. When the MED of carbon is assumed to be \$65, the MED component of the second best optimal tax is greater compared with cases in which the MED is \$5 and \$25.

The last column in Table 6 shows the second best carbon tax when there is a biofuel subsidy. The results follow the general trend that the carbon tax is lower with a subsidy relative to the case without a subsidy. An exception to the general trend is the case in which the elasticity of substitution among consumption goods is high. In this case, the subsidy's effect of lowering fuel prices leads to greater fuel consumption and less emissions reduction, leading to a slightly higher second best tax compared to scenarios without the subsidy. With a pre-existing subsidy, the second best optimal tax may be zero. In the case with a low elasticity of substitution between leisure and consumption, the revenue recycling effect is weak (as discussed earlier in this section). Thus, the negative effect of the subsidy coupled with the tax interaction effect of the carbon tax makes it welfare decreasing to impose a carbon tax.

For all the cases discussed above, the finding that the second best optimal carbon tax for fuel is lower with biofuel holds. We also tested sensitivity to the land rent tax rate, as well as the initial share of biofuel in the fuel mix, and found that our qualitative findings were unchanged; changes in these assumptions resulted in only marginal changes to our numerical results.

Conclusions

This paper analyzes the impact of biofuel and biofuel policies on the welfare effect of using a carbon tax to reduce GHG emissions in the fuel sector in the presence of distortionary taxes in the labor market. Consistent with the current literature, we find that a carbon tax on fuel not only increases welfare by internalizing externalities from carbon emissions but also by raising revenue that can be used to reduce distortionary labor taxes, resulting in a second best carbon tax that is higher than the MED. However, we find that in the presence of biofuel, the second best optimal carbon tax is 6–100% lower than in the case with gasoline as the only fuel, depending on the elasticity of substitution between the two fuels, on the emissions intensity of biofuel relative to gasoline, on other parameters governing the responsiveness of labor supply and fuel demand to the tax, and on whether or not a biofuel subsidy exists. The presence of biofuel in the fuel mix reduces the second best optimal carbon tax by increasing land rent and food prices, which in turn reduces labor supply. In addition, the availability of biofuel as a low-carbon substitute for gasoline increases the emissions reduction that occurs with an increase in the carbon tax, and leads to a greater erosion of the carbon tax base. These effects dominate the effect of biofuels in lowering fuel prices by reducing demand for gasoline. Overall, biofuels lead to a net increase in the negative tax interaction effect of the carbon tax relative to the case with gasoline as the only fuel.

The existence of biofuel support policies such as a biofuel subsidy further erodes welfare gains from carbon taxation by further increasing biofuel demand and adding to the burden of generating revenue through distortionary taxation. The results of this study strengthen the case for a carbon tax rather than a biofuel subsidy as an emissions reduction policy, since a carbon tax has both an output effect that reduces fuel demand, and a substitution effect that encourages a shift to biofuel, while a subsidy on biofuel only has the latter effect. In addition, a carbon tax has the potential to decrease taxation inefficiency while a subsidy exacerbates tax inefficiency by inducing more distortionary taxation.

Our results have several implications for broader energy policy in the presence of distortionary labor taxes. A carbon tax that induces substitution toward a cleaner good, and increases the price of other goods competing for inputs with the cleaner good, could worsen the tax interaction effect and lead to a lower second best optimal tax. For example, a revenue-neutral carbon tax imposed on the electricity sector could increase demand for pulpwood and mill residues for co-firing with coal in power plants and increase the price of forest products. The tax could also incentivize more natural gas based electricity generation and raise the price of natural gas and the cost of producing fertilizer and food crops. Thus, price changes in related markets should be considered in setting second best environmental taxes.

Due to the unpopularity of taxes, the government has typically offered subsidies to cleaner forms of energy such as wind and solar, rather than taxing all forms of energy according to the externalities they generate. Our results suggest that in the presence of a distortionary labor tax, these subsidies cause welfare losses by increasing the amount of distortionary taxation. In addition, if subsidies lower the overall price of energy they could worsen other energy externalties.

Our model assumes that agricultural land is limited and is appropriate for a land constrained economy. The availability of idle cropland and marginal land that could be used for biofuel production would minimize the negative effects of increasing land rent and food prices associated with biofuel. Our model does not include subsidies to agricultural crops which are an input to both biofuel and food production. To the extent that the carbon tax raises commodity prices and lowers the need for agricultural subsidies, its revenue recycling benefits would be enhanced. This would offset some of the negative tax interaction effect due to higher food prices and increase the second best optimal tax relative to what it would be in the absence of agricultural subsidies.

The framework developed here assumes that the environmental effect of the carbon tax depends only on changes in the US fuel market. Without a global carbon tax, international trade leads to leakage effects in which lower gasoline demand in the US decreases the world price of crude oil and increases gasoline consumption elsewhere in the world. In addition, increased biofuel production could also lead to land use change (such as deforestation) in other countries that would also increase emissions. If those effects were considered, then the environmental welfare gain owing to the carbon tax would be lower than that suggested by our model. The static framework presented here also precludes analysis of the potential for the carbon tax and biofuel subsidy to lead to a green paradox because they encourage inter-temporally optimizing fossil fuel producers to extract and sell their fuel more quickly and thereby paradoxically increase (rather than decrease) carbon emissions. There is a large literature analyzing the conditions under which a green paradox arises. The first best carbon tax at any point in time, however, is still shown to be equal to the present value of the marginal external damage caused in all future periods by present emissions (Van der Ploeg, 2013). Analysis of the second best carbon tax in the presence of pre-existing distortions in the labor market in a dynamic setting is left for future research. However, a dynamic setting is unlikely to affect the key insight from this paper that in the presence of pre-existing distortions in the labor market, a tax that incentivizes clean energy may cause other commodity prices to increase, and can worsen the tax interaction effect and cause the second best optimal tax to be lower than otherwise.

The optimal carbon tax in the presence of other renewable energy policies such as renewable mandates and a low carbon fuel standard (LCFS) is not discussed in this paper. These policies operate like an implicit tax on fossil fuels and subsidy on biofuel that is revenue neutral. However, their effects on GHG emissions are ambiguous (Ando et al., 2010; Chen et al., forthcoming; Holland et al., 2009). If these policies contribute to a reduction in emissions, their presence would lower the level of the carbon tax needed to internalize GHG externalities. Although a pre-existing mandate or LCFS policy will not affect the revenue implications of the carbon tax, these policies can affect the second best optimal tax because their presence leads to a smaller emissions tax base.

Our model only considers taxing carbon emissions in the fuel market. Extending the model to include economy-wide emissions will increase the base of the carbon tax, thus enhancing revenue generation from the tax. However, an economy-wide carbon tax could also lead to greater increase in the prices of inputs to clean energy production, worsening the tax-interaction effect. The net effect in this scenario has to be empirically determined by future research.

Appendix A

The change in V for a marginal change in T^C is

$$\frac{dV}{\lambda dT^C} = -E - \frac{\phi}{\lambda}\frac{dE}{dT^C} - \frac{\psi}{\lambda}\frac{dM}{dT^C} - L\frac{dT^L}{dT^C} + \left(\overline{N} - \frac{\partial P^B}{\partial R}B - \frac{\partial P^F}{\partial R}F\right)\frac{dR}{dT^C} \tag{A.1}$$

Total differentiation of the government budget constraint given by

$$Y = T^L L + T^C E + T^M M \tag{A.2}$$

gives the expression for the change in the labor tax for a marginal change in the carbon tax:

$$\frac{dT^L}{dT^C} = -\frac{1}{L}\left(E + T^C\frac{dE}{dT^C} + \frac{T^M}{\lambda}\frac{dM}{dT^C} + T^L\frac{dL}{dT^C}\right) \tag{A.3}$$

Substituting (A.3) in (A.1) yields (4).

Appendix B

The total amount of land is equal to the demand for land for biofuel and food production i.e. $\overline{N} = N_B + N_F$. We define a unit of land as the input necessary to produce one unit of B or F so that $N_B = B$ and $N_F = F$ and $\overline{N} = B + F$. The rental rate of land (R) can be interpreted as the marginal cost of the land constraint. Thus, a higher demand for land from either biofuel or food production will raise the value of R. For the purpose of the derivation below, we assume that labor and the labor tax rate are fixed.[14]

[14] Recall that in the utility function, leisure is weakly separable from consumption goods. This implies that the marginal rate of substitution between biofuel and food (or any pair of consumption goods) is independent of the quantity of leisure or labor (see Goldman and Uzawa, 1964, p. 388). Thus, given a change in relative prices of biofuel and food due to the carbon tax, the resulting change in demand for biofuel and food will be independent of the level of labor. In the case of the labor tax, a change in the labor tax rate due to a change in the carbon tax will affect the level of labor and consumption only through an "income effect", or a change in the overall expenditure for consumption goods (Deaton and Muellbauer, 1980, p. 128). Therefore, assuming that the consumption sub-utility function is homothetic, a change in T^L is unlikely to have an effect on the relative demand for B and F. If B and F have identical production functions, then a proportional change in both demands will not change their input demands for land and labor relative to each other. This can be shown by comparing the input demands of two goods with identical production functions in which the ratio of input demands depends only on the ratio of output levels.

Table C1
Consumption and input expenditure shares.

Share of leisure in utility	0.15
Share of consumption in utility	0.85
Share of fuel in consumption	0.03
Share of food in consumption	0.10
Share of other goods in consumption	0.87
Share of gasoline in fuel	0.92
Share of biofuel in fuel	0.08
Share of crude oil imports in gasoline production	0.60
Share of labor in gasoline production	0.07
Share of capital in gasoline production	0.33
Share of labor in biofuel production	0.37
Share of land in biofuel production	0.08
Share of capital in biofuel production	0.55
Share of labor in food production	0.40
Share of land in food production	0.01
Share of capital in food production	0.59
Share of labor in other goods production	0.74
Share of land in other goods production	0.00
Share of capital in other goods production	0.26

Note: Consumption and input expenditure shares are derived from the social accounting matrix. The α parameters in (9)–(15) are derived from these expenditure shares (see Rutherford, 1995). Utility is measured in dollar terms as the sum of the value of leisure hours and expenditures on consumption goods. The value of leisure hours is derived using labor supply elasticities and the value of consumption expenditures based on the method used by Fox (2002).

Taking the total differential of the first order conditions of G, B, and F and the additional constraint that $\overline{N}=B+F$, the following system of equations is obtained:

$$\begin{pmatrix} (U_M M_G)_G & (U_M M_G)_B & 0 & 0 \\ (U_M M_B)_G & (U_M M_B)_B & 0 & -1 \\ 0 & 0 & U_{FF} & -1 \\ 0 & 1 & 1 & 0 \end{pmatrix} \begin{pmatrix} \frac{dG}{dT^C} \\ \frac{dB}{dT^C} \\ \frac{dF}{dT^C} \\ \frac{dR}{dT^C} \end{pmatrix} = \begin{pmatrix} \delta^G \\ \delta^B \\ 0 \\ 0 \end{pmatrix}$$

The reader can confirm that the following expressions hold:

$$\frac{dG}{dT^C} = \frac{1}{|D|} U_{FF}\delta^G + \delta^G (U_M M_B)_B - \delta^B (U_M M_G)_B \tag{B.1}$$

$$\frac{dB}{dT^C} = -\frac{1}{|D|} \delta^G (U_M M_B)_G - \delta^B (U_M M_G)_G \tag{B.2}$$

$$\frac{dF}{dT^C} = \frac{1}{|D|} \delta^G (U_M M_B)_G - \delta^B (U_M M_G)_G \tag{B.3}$$

$$\frac{dR}{dT^C} = -\frac{U_{FF}}{|D|} \delta^G (U_M M_B)_G - \delta^B (U_M M_G)_G \tag{B.4}$$

where

$$|D| = (U_M M_B)_G (U_M M_G)_B - U_{FF}(U_M M_G)_G - (U_M M_B)_B (U_M M_G)_G \tag{B.5}$$

For the perfect substitutes case, the equations above simplify to

$$\frac{dG}{dT^C} = \frac{\delta^G U_{FF} + U_{MM}(\delta^G M_B M_B - \delta^B M_B M_G)}{M_G M_G U_{FF} U_{MM}} \tag{B.6}$$

$$\frac{dB}{dT^C} = \frac{1}{U_{FF}} \left(-\delta^G \frac{M_B}{M_G} + \delta^B \right) \tag{B.7}$$

$$\frac{dF}{dT^C} = -\frac{1}{U_{FF}} \left(-\delta^G \frac{M_B}{M_G} + \delta^B \right) \tag{B.8}$$

$$\frac{dR}{dT^C} = \delta^G \frac{M_B}{M_G} - \delta^B \tag{B.9}$$

where $U_{MM} = (dP^M/dM) = (P^M/\varepsilon^{MP}M)$, $\varepsilon^{MP} = (\partial M/\partial P^M)(P^M/M)$, $U_{FF} = (dP^F/dF) = (P^F/\varepsilon^{FP}F)$, and $\varepsilon^{FP} = (\partial F/\partial P^F)(P^F/F)$. Furthermore, B, G, M, P^G, P^B and P^F are market determined variables and ε^{MP} and ε^{FP} are elasticity estimates.

Appendix C

See Table C1.

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