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 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. The existence of a fixed biofuel subsidy further reduces the welfare gain from carbon taxation.

Keywords: carbon tax, optimal fuel tax, biofuel, second-best policy

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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 have shown that a tax on fuel is an effective and efficient instrument for reducing carbon emissions from gasoline use (West and Williams 2007; Parry and Small 2005). Holland, Hughes, and Knittel (2009) show this to be the case in the context of fuel being comprised of both gasoline and biofuel. 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). 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 an environmental tax to reduce the labor tax is not sufficient to compensate for its negative impact of worsening the distortion in the labor market and reducing the allocative efficiency of consumption (see Goulder (1995b) and Bovenberg (1999) for a comprehensive discussion). However, Parry (1995) argues that the second-best optimal tax could be higher than the MED if the taxed commodity is a relatively weak substitute for leisure. Parry and Small (2005) consider the case where gasoline is the only fuel and show that the second-best optimal tax rate for gasoline is above the Pigouvian tax rate since gasoline is a weak substitute to leisure.

This paper extends that literature by analyzing the second best optimal carbon tax for fuel in the presence of biofuel and pre-existing biofuel policies. Interest in biofuel as an alternative fuel source has grown rapidly in recent years. The lower carbon intensity of biofuel compared to gasoline expands the options for mitigating carbon emissions from simply reducing gasoline consumption and vehicle miles traveled to also displacing gasoline by biofuel. The availability of biofuel as a fuel source is likely to affect the design and magnitude of the optimal fuel tax. 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 will 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. [3] With the presence of biofuel in the policy mix, the fuel tax will affect the agricultural sector since biofuel production is land intensive and competes with other land-using production activities like agriculture for limited land inputs. Thus, a tax-induced change in biofuel production could affect the price of land or land rent; this in turn would affect income and the prices of goods (such as food) using land as an input. In the presence of a labor market distortion such as a labor tax, higher income and higher food prices add to the adverse effect of the tax induced increase in fuel prices on real wages and on labor supply. Thus, with biofuel included in the fuel mix, analysis of the welfare effects of a carbon tax requires the inclusion of the effects on the agricultural sector in addition to fuel and labor markets.

Policy makers have typically been reluctant to tax fuel and have instead preferred to subsidize biofuels. Until recently, corn ethanol production in the US was supported by a volumetric tax credit of $0.45 per gallon. The production of advanced biofuels continues to be supported by a tax credit of $1.01 per gallon. We analyze the welfare effects of a biofuel subsidy while recognizing the need to finance it using distortionary labor income

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

taxes. While the subsidy has the potential to reduce emissions by inducing displacement of gasoline by biofuels, it can impose welfare costs, not only by necessitating an increase in the labor income tax rate but also by raising land rents and food prices. Although previous studies (Khanna, Ando, and Taheripour 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.

Lastly, we examine the benefits of supplementing a biofuel subsidy with a carbon tax. While the carbon tax revenue can be used in part to finance the subsidy, the negative effects of a carbon tax on food prices and social welfare could also be exacerbated in the presence of other policies to support biofuels. Additionally, by promoting more biofuel production, the carbon tax could increase distortionary expenditures by the government on the subsidy. We examine the conditions under which it is optimal to impose a positive carbon tax in the presence of a pre-existing biofuel subsidy and compare its level to that in the absence of the subsidy.

We undertake this analysis by developing a framework that assumes that 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, but land use as an input is limited 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 rate, 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 and labor tax. In addition, we also 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 second best optimal carbon tax, as well as the market and welfare impacts of the carbon tax and biofuel subsidy.

Our analysis extends the model developed by Parry and Small (2005) by including both food and fuel sectors, land as a fixed factor, and examining the effect of the carbon tax not only on fuel prices but also food prices. We find like Parry and Small (2005) that the second best optimal carbon tax is likely to be higher than the MED even in the case with biofuel. However, the presence of biofuel in the fuel mix lowers the value of the second best optimal carbon tax relative to the case with gasoline only. The extent to which this occurs depends on the elasticity of substitution between the two fuels, the emissions intensity of biofuels relative to gasoline, and the other parameters governing the responsiveness of labor supply and fuel demand to the tax. The presence of biofuel in the fuel mix leads to a larger reduction in the emissions tax base and increase in food prices (due to increased competition for land input) in response to the tax than otherwise. As a result of both these effects, the tax interaction effect is greater in the presence of biofuels and the second best optimal carbon tax is lower than with gasoline only.

Our numerical model treats fuel as one of the goods within a consumption basket that includes food and other goods, resulting in a weaker elasticity of substitution between fuel and leisure than in Parry and Small (2005) who treat miles consumption and leisure as the only two goods . The magnitude of the second best tax, even in the gasoline only case in relation to the MED is larger than that obtained by Parry and Small (2005) due to the weaker elasticity of substitution between fuel and leisure, the presence of other inputs that are not perfectly mobile, and the smaller base for the carbon tax. We show the sensitivity of the second best optimal carbon tax both in the gasoline only case and the case with biofuels to assumptions about the elasticity of substitution between leisure and consumption, between fuels, and among consumption goods and production inputs.

Additionally, we show that in the presence of biofuels, the second best optimal carbon tax depends on the other pre-existing distortions such as a biofuel subsidy. The welfare gain from carbon taxation (and the second best optimal carbon tax) is lower due to the subsidy's effect of further increasing food prices and increasing the burden for the government to generate revenue through distortionary taxes. A biofuel subsidy by itself decreases carbon emissions; however miles externalities increase due to the higher overall fuel consumption relative to the case with no subsidy. In addition, the subsidy provision is socially costly. As a result, the value of carbon emissions reduction is only a quarter of the total welfare loss associated with the subsidy. Depending on the elasticity of substitution between gasoline and biofuel, imposing a carbon tax on top of a biofuel subsidy may or may not increase welfare; the second best optimal carbon tax is zero if gasoline and biofuel are close to perfect substitutes. Sensitivity analysis shows that the qualitative findings are robust to a wide range of parameter assumptions.

The paper proceeds as follows : Section 1 presents the analytical model and the derivation of the second best optimal carbon tax. In Section 2, we describe the numerical simulation used to obtain estimates of the second best optimal carbon tax and its market effects, as well as data and parameters used to calibrate the numerical model. Section 3 presents estimates of the second best optimal carbon tax, as well as market effects of the biofuel subsidy and carbon tax. The sensitivity analysis is also discussed. Section 4 concludes.

1 Analytical Framework

The representative consumer derives utility from leisure ($\acute{L}$) and consumption of food (F) which is a clean good, and fuel(f) which is a dirty good used to produce miles (M). [4] 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. The function $f(G, B)$ is sufficiently general to allow for a broad range of technological substitution possibilities between G and B (see Holland, Hughes, and

[4]The focus of this paper is the effect of a carbon tax specifically for fuel, thus we assume that GHG emissions from the food sector are zero. Proposed regulation to limit GHG emissions by setting a price on carbon typically focus on energy intensive sectors, and exclude agricultural production (EIA 2009)

Knittel (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 (CO2) equivalents. The representative consumer's utility function is:

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

where u is strictly concave. The MED of GHG emissions and miles externalities are denoted by ϕ and ψ, respectively. The utility function exhibits weak separability between leisure ($\acute{L}$) 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, $L = \overline{L} - \acute{L}$. The consumer also owns land (T) and derives income from land rent (R). The fixed total amount of land is denoted by $\overline{T}$. 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]

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

The government taxes labor, fuel and miles to obtain revenue. The tax on miles 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

[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 land rent would not change.

proportional to their GHG emissions, i.e., $T^i = T^C \delta^i$, $i = G, B$ and T^C is the carbon tax. The prices of gasoline, biofuel and agricultural goods 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 $P^M = \frac{G}{M}(P^G + T^G) + \frac{B}{M}(P^B + T^B) + T^M$. Thus, the consumer's budget constraint is:

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

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 $G = G(L^G), B = B(L^B, T^B)$ and $F = F(L^F, T^F)$.[7]

Maximizing (1) subject to (3) yields optimal consumption levels. Substituting the optimal quantities of $\acute{L}$, G, B, and F in the utility function yields the indirect utility function as a function of the carbon tax, income, and the vector of prices ($\mathbf{P}$): $V(T^C, I, \mathbf{P})$. 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 on the right hand side is the marginal benefit of reducing the level of environmental externality. The second and third terms reflect the change in the economy's tax base and the non-environmental welfare effect of a carbon tax. A reduction in the economy's tax base indicates greater inefficiency in the tax system as a device to generate revenue, as higher marginal tax rates are needed to generate the same amount of revenue. A carbon tax would erode the tax base on emissions (second term). Thus, the sign and

[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 i.e. $(K\frac{\partial R}{\partial T^C} - A\frac{\partial P^A}{\partial R}\frac{\partial R}{\partial T^C} - B\frac{\partial P^B}{\partial R}\frac{\partial R}{\partial T^C}) = 0$.

magnitude of the effect of the tax on labor supply (third term) determines whether the non-environmental effect of the tax is positive or negative.

From equation (4), an expression for the second-best optimal carbon tax is obtained [9]:

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

The first term is the MED corresponding to emissions, divided by the marginal utility of income, λ which is assumed to equal unity. 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 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 ($\frac{dE}{dT^C}$), the lower the magnitude of the second term in (5), implying that the more price elastic the taxed good is, the lower the magnitude of the non-environmental component of the tax in relation to the MED. Thus, a second best optimal carbon tax is more likely to be higher than the MED if levied on on a good that has lower price elasticity because in that case the tax will have a smaller tax base erosion effect.

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

[9] 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 this carbon tax rate corresponds to a second-best optimal labor tax rate, since both are jointly determined.

1.1 Effect of the Tax on Emissions

The magnitude of the effect of the tax on the level of emissions depends on the change in gasoline and biofuel demand induced by the tax. Using the definition of E provided above, the effect of a marginal increase in the tax on emissions is given by: $\frac{dE}{dT^C} = \delta^G \frac{dG}{dT^C} + \delta^B \frac{dB}{dT^C}$. The tax will decrease the level of gasoline consumption, since gasoline has a higher emissions intensity compared to biofuel. On the other hand, the tax could increase or decrease biofuel production depending on the substitutability between gasoline and biofuels, and their relative costs and GHG intensities. If gasoline and biofuel are perfect substitutes, the elasticity of demand for gasoline and biofuel with respect to the carbon tax is given by (see Appendix B for the derivation):

$$\epsilon^{GT} = \epsilon^{MP} \frac{T^G}{P^G} - \epsilon^{BT} \frac{B}{G} \tag{6}$$

$$\epsilon^{BT} = \epsilon^{FP} \frac{F}{B} \left[1 - \frac{\delta^B}{\delta^G} \right] \frac{T^C}{P^F} \tag{7}$$

The magnitude of ϵ^{GT} depends on the price elasticity of miles demand (ϵ^{MP}) as well the elasticity of biofuel demand with respect to the tax (ϵ^{BT}). In the absence of biofuel, the reduction in gasoline demand due to the tax is fully dependent on the extent to which miles demand decreases with the tax. However, if the tax increases biofuel demand, the potential to reduce gasoline demand is greater due to the possibility of substituting biofuel for gasoline. This implies that the presence of biofuel increases the potential for emissions reduction. While this increases the environmental benefit from carbon tax (first term in (4)), it also leads to a greater reduction in the carbon tax base. As shown in equation (5), if labor supply increases with the tax, a larger reduction in emissions lead to a smaller benefit in terms of increasing the efficiency of the tax system. Thus the non-environmental benefit of a carbon tax will be smaller in the presence of biofuels because the tax base erosion due to the tax will be larger.

The term inside the square brackets in (7) shows that if the ratio of the emissions intensity of biofuel and gasoline is less than one, i.e. biofuel has a lower emissions intensity compared to gasoline, the carbon tax increases biofuel demand ($\epsilon^{BT} > 0$). As the ratio becomes smaller, the carbon tax leads to a larger increase in biofuel demand. Equation (7) also shows that a higher elasticity of demand for food ($-\epsilon^{FP}$) increases the magnitude of ϵ^{BT}. This is because biofuel competes with food for land input. As biofuel production increases with the tax, land rent and food prices go up. A higher elasticity of demand for food would result in a greater reduction in food production and freeing up of land for biofuel production as food prices increase.

The relationship between biofuel demand and land rent is given by (see Appendix B):

$$\frac{dR}{dT^C} = -\frac{P^F}{-\epsilon^{FP} F} \frac{dB}{dT^C} \tag{8}$$

Since the price elasticity of food demand ($-\epsilon^{FP}$) is negative, the sign of $\frac{dR}{dT^C}$ depends on whether the tax increases or decreases biofuel demand. If $\frac{dB}{dT^C} > 0$, then $\frac{dR}{dT^C}$ is positive, and vice-versa. Equation (8) shows that the more price elastic food demand is, the lower the change in land rent due to the tax. The carbon tax induced increase in biofuel production would therefore have a smaller negative impact on food prices and a smaller tax interaction effect in this case.

1.2 Effect of the Tax on Labor Supply

Labor supply is a function of the exogenous variables in the indirect utility function. Noting that $I(T^L, R)$ and $\mathbf{P}(R)$, the change in labor supply for a marginal change in T^C can be expressed as:

$$\frac{dL}{dT^C} = \frac{\partial L}{\partial T^L}\frac{dT^L}{dT^C} + \frac{\partial L}{\partial T^C} + (\frac{\partial L}{\partial R} + \frac{\partial L}{\partial \mathbf{P}}\frac{d\mathbf{P}}{dR})\frac{dR}{dT^C} \tag{9}$$

The first term on the RHS 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 supply. The second term is the tax interaction effect which is the partial derivative of the 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. Due to the presence of biofuels in the fuel mix, the carbon tax also affects land rent, as tax-induced changes in biofuel production affect competition for land inputs. A change in land rent affects the price of food, and also affects land rent 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 (9) has a negative impact on labor supply.

2 Numerical Simulation

In order to quantify the impact of biofuels on the second-best optimal carbon tax for fuels, a numerically solved general equilibrium model is developed. This model is used to obtain estimates of T^{C*} under different policy scenarios and different composition of fuel, as well as market impacts of a carbon tax and a biofuel subsidy.

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 (CO) is also introduced as a fixed input to gasoline production. [10] Crude oil is assumed to be an imported good. The prices of labor and capital are fixed, while prices of land and crude oil are endogenously determined. We also relax the assumption that the government cannot tax land rent. Finally, an additional consumption

[10]The presence of a fixed factor in the production of a taxed good will affect the second best optimal tax since it will lower the tax interaction effect due to the tax and increase the second best optimal tax (Bento and Jacobsen, 2005). Since this fixed factor is present whether or not biofuel is in the fuel mix, it is unlikely to affect the relative magnitudes of second best optimal tax with and without biofuel.

good, O for other goods is added to model the size of the fuel and food sectors relative to the level of consumption in the US economy.

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

$$U = \alpha_{U\acute{L}} L^{\frac{\sigma_U - 1}{\sigma_U}} + \alpha_{UC} C^{\frac{\sigma_U - 1}{\sigma_U}} \tag{10}$$

$$C = \alpha_{CM} M^{\frac{\sigma_C - 1}{\sigma_C}} + \alpha_{CF} F^{\frac{\sigma_C - 1}{\sigma_C}} + \alpha_{CO} O^{\frac{\sigma_C - 1}{\sigma_C}} \tag{11}$$

$$M = \alpha_{MG} G^{\frac{\sigma_M - 1}{\sigma_M}} + \alpha_{MB} B^{\frac{\sigma_M - 1}{\sigma_M}} \tag{12}$$

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 denote the share of expenditures allocated to leisure and consumption goods.

The consumer purchases consumption goods and obtains revenue by supplying labor, land and capital 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 tax on fuel consist 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 externalities per unit of fuel consumed.

The government budget constraint is given by :

$$Y = T^L W L + T^K R T + (T^{G'}) P^G G + (T^{B'}) P^B B \tag{13}$$

with $T^{G'}$ and $T^{B'}$ denoting tax rates for gasoline and biofuel including both carbon and miles tax. We also consider a case in which the government provides a subsidy to biofuel consumption. With the subsidy, the term $SP^B B$ 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:

$$G = \gamma_G(\alpha_{GCO}CO_G^{\frac{\sigma_G-1}{\sigma_G}} + \alpha_{GL}L_G^{\frac{\sigma_G-1}{\sigma_G}} + \alpha_{GK}K_G^{\frac{\sigma_G-1}{\sigma_G}}) \tag{14}$$

$$B = \gamma_B(\alpha_{BL}L_B^{\frac{\sigma_B-1}{\sigma_B}} + \alpha_{BT}T_G^{\frac{\sigma_B-1}{\sigma_B}} + \alpha_{BK}K_B^{\frac{\sigma_B-1}{\sigma_B}}) \tag{15}$$

$$F = \gamma_F(\alpha_{FL}L_F^{\frac{\sigma_F-1}{\sigma_F}} + \alpha_{FT}T_F^{\frac{\sigma_F-1}{\sigma_F}} + \alpha_{FK}K_F^{\frac{\sigma_F-1}{\sigma_F}}) \tag{16}$$

$$O = \gamma_O(\alpha_{OL}L_O^{\frac{\sigma_O-1}{\sigma_O}} + \alpha_{OT}T_O^{\frac{\sigma_O-1}{\sigma_O}} + \alpha_{OK}K_O^{\frac{\sigma_O-1}{\sigma_O}}) \tag{17}$$

Finally, equilibrium requires market clearing in goods and factor markets.

2.1 Data and Calibration

The level of consumption and availability of factor inputs is 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). The fuel and food sectors were disaggregated from total consumption. The share of food in total consumption is 10% based on the expenditure share of of food consumption reported by the Bureau of Labor Statistics (BLS 2010) and the US Department of Agriculture (USDA 2000). Based on USDA's estimates, we assume that the share of farm value in food expenditures is 20% (Schnepf 2009). Land rent or leasing costs account for 5% of agricultural cost (Crago et al. 2010). The value of the fuel sector, as well as the share of biofuel 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 (NEB 2009). All prices are normalized to 2004 prices. The data indicate that fuel expenditures are 3% of total expenditures and biofuel accounts for 8% of fuel supply on an energy equivalent basis. The share of crude oil expenditures in gasoline production is 0.82, based on the share of crude oil in the pre-tax price of gasoline (Cohen 2011). Based on EIA data, we assume that 70% of crude oil used for gasoline production in the US is imported (EIA 2011).

Because one of the main effects of biofuel on the value of the carbon tax arises from the effect of biofuel demand on land rent, the share of land resources used for biofuel production in total land available $\frac{T_B}{T}$ is an important parameter, along with the share of expenditures on land input (α_{BL}) relative to expenditures on other inputs to biofuel production. The share of land, labor and capital inputs that go into biofuel production are derived from detailed estimates of production costs for corn ethanol that separate agricultural and refinery costs. Based on Crago et al. (2010), land used for biofuel production is 4% of total cropland in the US and expenditures on land input account for 8% of the value of biofuel production.

The top level utility function 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. We use labor supply elasticities of $\epsilon^C_{LL} = 0.2$ for compensated labor supply elasticity and $\epsilon_{LL} = 0.33$ for uncompensated labor supply elasticity. These values are similar to those used by Parry and Small (2005) based on Blundell, Duncan, and Meghir (1998) and Fuchs, Krueger, and Poterba (1998). Based on Parry (2001) and Bento and Jacobsen (2007), the tax rate on labor, T^L is set to 0.4. Following Bento and Jacobsen (2007), we use a land tax rate of 10% as a central estimate and conduct sensitivity analysis using other values of the tax rate on land rent. For the case with a pre-existing subsidy, the subsidy rate of 0.2 is 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.

For the elasticity among consumption goods, we use a central value of 0.1 and examine sensitivity to values of 0.05 and 1 in the sensitivity analysis. The low elasticity of substitution among consumption goods is consistent with empirical estimates that show inelastic demands of fuel and food (ERS 2003; Greene and Ahmad 2005). For the elasticity between biofuel and gasoline, we report results using a range of 1 to 10 and use 5 as the central value. For the elasticity of substitution between factors of production we use 0.5 as the central value and test sensitivity to values of 0.1 and 1.

2.1.1 Externality cost and GHG intensity of fuels

Parry and Small (2005) distinguish between external costs of gasoline that are associated with fuel and those associated with miles consumption. They report that the marginal external damage associate with miles: air pollution, congestion and accidents are \$0.32, \$0.18, and \$0.27 respectively per gallon of gasoline. We therefore impose a miles externality cost of \$0.77 per gallon. Parry and Small (2005) also review the existing literature on the cost of carbon emissions and conclude that there exists a wide range of estimates ranging from \$0.7 per ton to more than \$100 per ton of carbon. Parry and Small (2005) use \$25 per ton of carbon as the MED of carbon emissions. In our case, we follow the language of current regulatory proposals which taxes emissions based on carbon dioxide (CO2) content. The proposed American Clean Energy and Security (ACES) Act in June 2009 would have established a cap-and-trade program for GHG emissions. The carbon prices expected to prevail with the implementation of the ACES Act in the base case analyzed by the EIA (2009) range from \$20 per metric ton of CO2 in 2010 to \$65 per metric ton of CO2 in 2030 and onwards. Thus, we use an MED of \$25 per ton of CO2.

The externality impact of a gallon of fuel is measured using its GHG intensity, which is defined as the amount of GHG in CO2 equivalents (eq) emitted per unit consumption of fuel. Unlike Parry and Small (2005) who used tailpipe emissions of gasoline, which amount to about 9 kg CO2-eq (2.4 kg carbon-eq) per gallon, we use emissions from Life Cycle Assessment (LCA) studies that measure emissions from "well-to-wheel" or from the production of inputs that go into fuel production, up 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, up through end of pipe emissions [11]. Since the GHG reduction capacity of biofuel relative to gasoline is an important consid-

[11] Some studies have suggested that emissions from indirect land use change (ILUC) may be a significant source of emissions (Searchinger et al. 2008; Fargione et al. 2008). However, ILUC emissions cannot be specified ex-ante because its value depends (in part) on the magnitude of the fuel tax on carbon. Measures

eration, LCA provides a better meausure of the two fuels' relative GHG intensities. GHG emissions from gasoline are fairly well established. We use a GHG intensity of 12.05 kg CO2-eq per gallon of gasoline based on CARB (2009). The assumed MED of a ton of CO2 and the GHG intensity of gasoline imply that the MED of emissions is $0.3 per gallon of gasoline. [12] 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 has 12-20% less emissions than gasoline (Farrell et al. 2006; Wang, Wu, and Huo 2007). More recent studies with more technologically advanced refineries suggest a reduction of over 40% (Liska et al. 2009). For the GHG intensity of biofuel, we use a range suggested by current studies for corn ethanol. In the central case, we assume that biofuel has a GHG intensity of 4.8 kg CO2-eq per gallon, which implies a 40% reduction in emissions compared to an energy equivalent unit of gasoline. [13] In the sensitivity analysis we consider cases in which the emissions intensity of biofuel are 6.8 kg CO2-eq per gallon and 3.7 kg CO2-eq per gallon, implying that biofuel reduces emissions by 20% and 60%, compared to gasoline.

A positive externality associated with biofuel is its potential to reduce imports of crude oil, which in turn provides energy security benefits to the US. Estimates of the energy security costs that arise from monopsony rents of oil cartels and economic costs of supply disruptions range from $0.03 to $0.16 per gallon (Leiby 2002, 2007). Based on the estimates reported in Leiby (2002), we assume that the energy security benefit associated with replacing a gallon of gasoline with domestically produced fuel is $0.12 per gallon. It is not clear that an energy equivalent gallon of biofuel necessarily replaces imported gasoline. Thus, we assume that an energy equivalent unit of biofuel provides energy security benefits equal to replacing half a unit of gasoline.

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of ILUC are also subject to significant uncertainty, and its implications for regulation is still under debate (Khanna, Crago, and Black 2011; Khanna and Crago forthcoming). Thus, we exclude ILUC emissions in the measurement of GHG intensity.

[12]Since Parry and Small (2005) use the carbon content of gasoline (rather than CO2 content), their calculated MED of emissions is $0.06 per gallon, assuming an MED of $25 per ton carbon.

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

3 Results

3.1 Second best optimal carbon tax

Table 1 shows the second best optimal carbon tax for the fuel sector in cases with gasoline as the only fuel for transportation and with both gasoline and biofuel as fuels. Results are presented under alternative assumptions about the elasticity of substitution between the two fuels (σ_M). We also analyze the second best taxes with a pre-existing biofuel subsidy and with a value being attached to the energy security benefits of biofuels. We find that when the marginal external damage of carbon is assumed to be \$25 per ton of CO2, the second best optimal carbon tax is \$100 per ton. The large second best tax relative to the MED is due to low elasticity of substitution between consumption goods. In addition, the presence of the fixed factor (crude oil) in the production of gasoline also contributes to weakening the tax interaction effect, as in Bento and Jacobsen (2007). Like Parry and Small (2005) we find that the second best optimal carbon tax is larger than the MED. With an MED per gallon fuel of \$0.83, they find the second best optimal gasoline tax to be \$1.01 per gallon, implying that the second best tax is 22% higher than the MED. Whereas Parry and Small (2005) consider a marginal change in the per gallon fuel tax (based on miles and emissions externalities), we consider a carbon tax that is levied only on the carbon content of the fuel; thus the increase in fuel price due to the tax is smaller. The smaller tax-induced increase in fuel price in our case leads to a weaker tax interaction effect, thus leading to a larger second best optimal tax relative to the MED. In the presence of biofuels in the fuel mix, a marginal increase in the carbon tax increases competition for land, which increases land rent and food prices. The tax also raises fuel prices; however this effect is smaller than in the case with gasoline only. For biofuel, the per unit tax is lower due to its lower emissions intensity. In the case of gasoline, a reduction in its demand decreases the price of the fixed factor (crude oil), which in turn decreases the marginal cost of gasoline production. Nevertheless, the tax interaction effect is larger than in the case with gasoline only and the second best optimal carbon tax ranges from \$85 to \$97.5 per ton, which is 2.5%-15% lower than the gas only case, depending on the elasticity of substitution between gasoline and biofuels. The reduction in the carbon tax is larger with a higher elasticity of substitution between gasoline and biofuel due to the larger shift towards biofuel consumption which in turn leads to higher food prices. A higher elasticity of substitution also increases emissions reduction due to greater displacement of gasoline and increases the tax base erosion that occurs with a carbon tax. Thus the welfare costs of the carbon tax are lower (see second term in (4)), and the magnitude of the non-environmental component of the second best tax is smaller when the elasticity of substitution between gasoline and biofuels is higher (5).

The following section discusses the underlying market changes that underpin the result that the second best optimal carbon tax is lower with biofuel in the fuel mix. In order to show the different market impacts due to the presence of biofuel, we simulate the effect of increasing the carbon tax from the Pigouvian level of \$25 per ton CO2 to \$50 per ton CO2. The results are in Table 2. The scenarios considered are similar to those in Table 1. These include the case with gasoline as the only fuel in column 2 and the case with gasoline and biofuels under two alternative assumptions about σ_M equal to 5 and 10 in columns 3 and 4. We show the effect of a biofuel subsidy by itself, assuming that no fuel tax exists, and the subsidy rate increases from 0 to 0.2 (column 5). Finally, we examine the effects of doubling the carbon tax with a pre-existing biofuel subsidy rate of 0.2 (column 6). The results in Table 2 illustrate our main hypothesis that the presence of biofuel in the fuel mix leads to a greater increase in land rent and food prices, as well as a larger decrease in emissions in response to a carbon tax compared to the case with gasoline as the only fuel. [14] The reduction in the emissions tax base and the increase in food prices reduce labor supply, leading to a lower second best optimal carbon tax.

With gasoline as the only fuel, a doubling of the carbon tax reduces fuel use and emissions by 1.59%. The reduction in demand for gasoline frees up labor and capital for use in other

[14]The price of other goods (O) increase as well, but the price increase is very small.

production activities and decreases their price 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 the land using sectors increase 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 only accounts for less than 1% of the cost of food production. Increased food and fuel prices decreases labor supply. However, the net effect of the carbon-labor tax swap is to increase labor supply and decrease the labor tax rate by 7.9%.

With biofuel in the fuel mix, gasoline consumption decreases by 2.85% while biofuel consumption (on an energy equivalent basis) increases by 16.33%. As discussed in Section 2, the presence of biofuel increases the potential for gasoline consumption to decrease with a carbon-based fuel tax due to the availability of a relatively less carbon intensive substitute. The reduction in fuel emissions is 1.85% which is greater by 16% compared to the gas only case. The increase in biofuel production increases competition for land and increases land rent by 2.04%, 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. The larger reduction in the tax base for carbon, as well as the larger increase in food prices due to higher land rent both lead to a stronger tax interaction effect. Thus, the change in the labor tax (-6.75%) is lower by 14% compared to the case with only gasoline.

An increase in the 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 a carbon tax. Under the assumption that $\sigma_M = 10$, gasoline consumption decreases by 3.32% while biofuel consumption increases by 21.64%. As shown in the fourth column of Table 2, this case leads to emissions reduction of 1.98%, which is 24% greater than the gas only case. The higher level of biofuel consumption leads to a greater increase in land rent. Land rent increases by 2.56% and 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 case with

$\sigma_M = 5$. A larger reduction in the emissions tax base and the higher increase in food prices lead to a higher tax interaction effect. Thus, the labor tax rate decreases by 6.44% which is 18% lower than the case with only gasoline.

3.2 Biofuel Subsidy

In this section, we compare the effect of a carbon tax to a policy of subsidizing biofuel. A biofuel subsidy increases biofuel consumption and decreases gasoline demand. An increase in the subsidy rate from zero to 0.2 decreases gasoline demand by 2.8% and increases biofuel demand by 43.45%. Due to the large increase in biofuel consumption relative to the cases in which a carbon tax is imposed, the reduction in emissions is smaller, at 0.47%. Unlike a carbon tax, a subsidy decreases the price of fuels. The consumer price of biofuel is 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 (equal to its marginal cost of production since there is no tax) decreases due to the reduction in its marginal cost as the 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, the price of food also increases due to the increase in land rent. The net effect is a marginal (0.01%) increase in labor supply. The provision of the subsidy necessitates an increase in the labor tax rate to keep government revenue constant. Thus, although the labor tax base expands, the reduction in the carbon tax base and the additional revenue requirement of the subsidy lead to an increase of 0.49% in the labor tax rate.

3.2.1 Second best optimal carbon tax with pre-existing subsidy

A pre-existing subsidy on biofuel affects the magnitude of the tax interaction effect in two ways: first, it increases the tax burden of increasing biofuel consumption because each unit of additional biofuel in the economy increases government expenditure to finance the subsidy. Second, the subsidy on biofuel increases the incentive to consume biofuel instead of gasoline, thus increasing the level of emissions reduction and also increasing the negative land rent effect due to biofuel. Compared to the case with no subsidy (Table 2, column 3), the increase in land rent (3.33%) is 63% higher, and the reduction in the labor tax rate is lower by 22%. As discussed in the analytical framework, a larger increase in the price of consumption goods reduces real wages, and hence reduce labor supply. In addition, a greater reduction in emissions strengthens the tax interaction effect by lowering the tax base on emissions. Both these effects lower the second best optimal tax.

If a pre-existing subsidy rate of 0.2 is provided to biofuel, the second best optimal carbon tax decreases to \$62.5, which is lower by 38% compared to the case with gasoline only. The second best optimal carbon tax decreases to zero if $\sigma_M = 10$; in this case the welfare cost of providing the additional subsidy to a tax induced increase in biofuels is greater than the welfare gains from reducing emissions and increasing the efficiency of the tax system via a carbon-labor tax swap. If the positive external benefits of biofuel in enhancing energy security is valued, it partially offsets the negative welfare impact of biofuels on food prices. With $\sigma_M = 5$, the second best tax is lower by 7% at \$90 per ton, compared to \$97.5 per ton without energy security benefits.

3.3 Fuel Taxes

Table 3 shows per gallon fuel taxes on carbon corresponding the type of fuel, for the cases examined above. The values in Table 3 correspond to the central case with the elasticity of substitution between gasoline and biofuel equal to 5, and the emissions intensity of biofuel is 40% lower than that of gasoline. 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, gasoline taxes on carbon range from

$1.52 to $1.85 per gallon, which is a reduction of 6%-23%, compared to the gas only case. Biofuel has a lower fuel tax on carbon compared to gasoline because its GHG intensity per gallon is lower. Biofuel taxes range from $0.8 to $0.92 per gallon. Consistent with the derived second best optimal carbon tax, the fuel tax in the presence of a pre-existing subsidy is lower, and if energy security benefits of biofuel are valued, the second best tax is larger compared to case that excludes those benefits.

3.4 Welfare Effects

We now discuss the welfare effect of the different policies discussed above. Table 4 shows the welfare effect of imposing the second best optimal carbon tax on fuel consisting only of gasoline, as well as gasoline and biofuel, relative to welfare when the carbon tax is equal to the MED of $25 per ton CO2. The elasticity of substitution between fuels is 5. For the case with biofuel, cases with and without a pre-exising subsidy, as well as the welfare effect of increasing the biofuel subsidy rate from 0 to 0.2 is also presented. Fuel externalities include miles and carbon externalities from fuel use, and the value of the change in externalities is obtained by calculating the product of the level of externality with its respective MED. The net welfare gain from imposing the second best optimal carbon tax is $18.9 billion, or 0.16% higher than when the tax is set equal to the MED. Imposing a carbon tax of $100 in the gas only case leads to the greatest increase in social surplus and reduction in fuel externalities. Imposing the second best optimal carbon tax with biofuel and gasoline leads to a lower increase in social surplus and lower reduction in fuel externalities because of the negative welfare effects (increase in food price, increased reduction in carbon tax base) due to biofuel. Since the second best optimal carbon tax is lower with biofuel compared the case with only gasoline, the decrease in fuel consumption (and fuel externalities) is lower. The net welfare gain is $12.8 billion or 0.11% higher than if the tax is equal to the MED.

Imposing a biofuel subsidy decreases social surplus as shown in Table 4 (column 4). Although emissions decrease by 47%, the externality gain is only $288 million which is only about a quarter of the net welfare loss (-\$1.13 billion). Total fuel use increases by 1%, leading to an increase in miles related externalities. The cost of increased miles externalities offset the welfare gain from reduced emissions. Thus the net environmental and social surplus effect of a biofuel subsidy is negative. The result in the last column indicates that imposing a carbon tax in the presence of a pre-existing subsidy may increase welfare, although the welfare effect from the tax (\$3.7 billion) is smaller compared to the case without a subsidy. However, this is not always the case. The results in Table 1 show that the optimal tax may be zero if the elasticity of substitution between gasoline and biofuel is higher, implying that welfare will decrease if a carbon tax is imposed on top of a biofuel subsidy.

3.5 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 5. In the base case with biofuels, the elasticity of substitution between gasoline and biofuel is 5 and biofuel is assumed to reduce emissions by 40% on an energy equivalent basis.

Increasing substitution among consumption goods (σ_C) to 1 leads to a greater reduction in the fuel tax base, thus the tax interaction effect is stronger and the second best tax is lower by 45%, compared to the base case. Greater substitution between goods also leads to a lower impact of biofuels on the carbon tax because consumers are able to switch away from consumption of land-intensive consumption goods like food to consumption of other goods. Conversely, setting σ_C to a lower value of 0.05 increases the second best tax.

The elasticity of substitution between leisure and consumption goods (σ_U) affects the extent to which labor supply responds to a change in the labor tax rate and the price of consumption goods. The change in the quantity of leisure for a marginal change in the fuel price is given by $\frac{\partial \acute{L}}{\partial P_f} = \frac{\partial \acute{L}}{\partial P_C}\frac{f}{C}$. A higher σ_S implies that $\frac{\partial \acute{L}}{\partial P_C}$ is larger, i.e. leisure (labor supply) increases (decreases) more with a tax-induced increase in the price of fuel. On the other hand, leisure and labor supply are also directly affected by the change in real wage when revenue from carbon taxes is used to reduce the labor tax rate. Thus, unless labor supply responds more to a change in the price of fuel, rather than the wage rate ($\frac{\partial \acute{L}}{\partial T^L} < \frac{\partial \acute{L}}{\partial P_C}\frac{f}{C}$), a higher value of σ_U will lead to a greater value of the second best tax, as shown in Table 5.

The elasticity of substitution between production inputs affects the extent to which the quantity of produced goods changes in response to changes to its own and other goods' prices. With a lower elasticity of substitution between the inputs ($\sigma_G = 0.1$) for gasoline production, there is a lower reduction in gasoline consumption (and emissions), thus the second best tax is larger. The opposite occurs if the elasticity of substitution between production inputs is higher ($\sigma_G = 1$): 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 larger 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. The larger reduction in the emissions tax base and the higher increase in food prices lead to a stronger tax interaction effect. Thus, the second best optimal carbon tax is 11% lower than in the base case. If emissions intensity of biofuel is 20% lower than that of gasoline, the second best tax is 11% higher than the base case.

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

4 Conclusions

The results of this paper highlight the impact of biofuel and biofuel policies on the welfare effect of using a carbon tax to reduce GHG emissions in the fuel sector. Consistent with the current literature, 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. However, we find that in the presence of biofuel, the second best optimal carbon tax is 2% - 38% lower than in the case with gasoline as the only fuel, depending on the assumed GHG emissions of biofuel, elasticity of substitution between gasoline and biofuel, and whether a biofuel subsidy exists. The presence of biofuel in the fuel mix reduces welfare gains from the carbon tax due to the tax-induced increase in land rent and food prices, as biofuel production increases. In addition, the availability of biofuel as a low-carbon substitute for gasoline increases the emissions reduction that occurs with the 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, and lead to a net increase the negative tax interaction effect of the carbon tax relative to the case with gasoline alone. 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 driving, and a substitution effect that encourages a shift to biofuel, while a subsidy on biofuel only has the later effect. In addition, a carbon tax has a positive non-environmental benefits while a subsidy decreases social surplus and increases miles externalities.

Our model assumes that agricultural land is limited and is appropriate for a land constrained economy such as the US. 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 also does not consider the effect of the carbon tax and biofuel subsidy on subsidies to agricultural goods which are an input to both biofuel and food production. To the extent that the carbon tax raises commodity prices and lowers the demand for food, it lowers the need for agricultural subsidies; therefore, its revenue recycling benefits would be enhanced. This could 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 these pre-existing subsidies.

The framework developed here assumes that the environmental effect of the carbon tax only depends on changes in the US fuel market. In the absence of 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 also increases emissions. If those effects were considered, then the environmental welfare gain owing to the tax would be lower than that suggested by our model.

Other policies to reduce carbon emissions in the fuel market, such as renewable mandates and a low carbon fuel standard (LCFS) are not discussed in this paper. One could view policies like a mandate and an LCFS as an implicit tax on carbon and subsidy on biofuel. These policies lead to similar incentives for consumers in terms of their fuel consumption (and the resulting GHG emissions). However, these policies do not generate or expend revenue, and thus would have different welfare consequences compared to the carbon tax and biofuel subsidy policies considered here. We do find that our results for the case with a carbon tax and biofuel subsidy are consistent with the findings in the literature that with a mandate or LCFS, gasoline demand decreases while biofuel demand increases, so the net effect on emissions is ambiguous (Holland, Hughes, and Knittel 2009; Ando, Khanna, and Taheripour 2010).

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 lowering the tax base erosion effect of the tax. However, an economy-wide carbon tax may also lead to greater demand for land-using renewable energy (in addition to biofuel), which could worsen the food price effects identified here. The net effect in this scenario has to be empirically determined by future research.

Table 1: Second-best optimal carbon tax ($/ton CO2)

	Gas only	Gas and Biofuel		
Elasticity of substitution between fuels		1	5	10
Carbon Tax	100	97.5	87.5	85
Carbon Tax with Subsidy	-	90	62.5	0
Carbon Tax with Energy Security	-	97.5	90	87.5

Table 2: Market and externality effects of alternative policies (% Change)

	Gas Only	Gas and Biofuel			
				Subsidy Only	Tax and Subsidy
Elasticity of substitution between fuels		5	10	5	5
Emissions	-1.59	-1.85	-1.98	-0.47	-1.95
Gasoline quantity	-1.59	-2.85	-3.32	-2.80	-3.71
Biofuel quantity	-	16.33	21.64	43.45	22.79
Gasoline price	21.45	17.30	15.83	-7.85	15.23
Biofuel price	-	13.15	17.95	-0.15	9.76
Food price	0.01	0.02	0.03	0.04	0.03
Land rent	0.68	2.04	2.56	3.70	3.33
Labor tax rate	-7.90	-6.75	-6.44	0.49	-5.28
Labor supply	0.43	0.38	0.37	0.01	0.31

Note: Numbers are % changes for an increase in the carbon tax from $25 per ton CO2 to $50 per ton CO2.

Table 3: Second best optimal fuel taxes ($/ gallon)

	Gas only	Gas and Biofuel	
Carbon Tax	1.97	1.82	0.91
Carbon Tax with Subsidy		1.52	0.80
Carbon tax with Energy Security		1.85	0.92

Note: The fuel tax in the gas only case corresponds to the second best optimal carbon tax with gas only in Table 1. With gasoline and biofuel, the carbon tax corresponds to the case with the elasticity of substitution between fuels equal to 5.

Table 4: Welfare change from imposing the second best optimal carbon tax (million dollars, in 2004 prices)

	Gas Only	Gasoline and Biofuel		
		Tax	Subsidy Only	Tax and Subsidy
Social Surplus	8689	6915	-541	1673
	(0.07)	(0.06)	(-0.005)	(0.01)
Gain from reduction of fuel externalities	10271	5980	-596	1434
	(6.61)	(3.87)	(-0.64)	(0.92)
Net welfare	18960	12895	-1137	3720
	(0.16)	(0.11)	(-0.01)	(0.03)

Note: Numbers in parenthesis are percentage changes from the welfare level with the carbon tax equal to \$25 per ton CO2. The fuel tax on miles externalities, which is equal to \$0.77 per energy equivalent gallon is held constant.

Table 5: Sensitivity analysis of second best carbon tax ($/ton CO2, in 2004 prices)

	Gas Only	Gas and Biofuel
Base case	**100**	**87.5**
Elasticity of substitution among consumption goods		
Low 0.05	112.5	92
High 1	55	52.5
Elasticity of substitution between leisure and consumption goods		
Low 0.5	77.5	72.5
High 2	112.5	102.5
Elasticity of substitution among production inputs		
Low 0.1	110	102.5
High 1	97.5	82.5
Reduction in emissions from biofuel		
Low 20%	NA	97.5
High 60%	NA	77.5
Marginal External Damage of CO2		
Low 100	105	97.5
High 150	108	102.5

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Appendix A

Deriving the effect of the carbon tax on indirect utility (V):

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

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

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 labor tax for a marginal change in the carbon tax:

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

Substituting this in A.1 yields (4).

Appendix B

The total amount of land is equal to the demand for land for biofuel and agricultural production i.e. $\overline{T} = T_B + T_F$. We define a unit of land as the input necessary to produce one unit of B or F so that $T_B = B$ and $T_F = F$ and $\overline{T} = B + F$. 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 agricultural production will raise the value of R. In order to obtain an expression for $\frac{dR}{dT^C}$, the change in the equilibrium values of B and F given a marginal change in T^C and its resulting impact on R have to be determined.

For the purpose of deriving the change in land rent with respect to the carbon tax, we assume that labor and the labor tax rate are fixed [15].

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

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

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:

[15] 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) page 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 rate 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) page 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 idential production functions in which the ratio of input demands depends only on the ratio of output levels.

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

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

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

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

where $U_{MM} = \frac{dP^M}{dM} = \frac{P^M}{\epsilon^{MP} M}$, $\eta^{MM} = \frac{\partial M}{\partial P^M} \frac{P^M}{M}$, $U_{FF} = \frac{dP^F}{dF} = \frac{P^F}{\epsilon^{FP} F}$, and $\epsilon^{FP} = \frac{\partial F}{\partial P^F} \frac{P^F}{F}$. Furthermore, B, G, M, P^G, P^B and P^F are market determined variables and ϵ^{MP} and ϵ^{FP} are elasticity estimates. Based on first order conditions representing the market condition that there is a fuel tax and biofuel subsidy, $M_B = \frac{P^G}{P^M}$ and $M_G = \frac{P^B}{P^M}$. If G and B are perfect substitutes and are defined as energy equivalent, $\frac{M_B}{M_G} = 1$.