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WELFARE IMPLICATIONS OF THE RENEWABLE FUEL STANDARD WITH A REVENUE-NEUTRAL TAX

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Abstract

We assess the welfare implications of imposing a revenue-neutral tax in the presence of the Renewable Fuel Standard (RFS). In our theoretical model, we identify a new welfare effect when imposing a revenue-neutral tax on a dirty input that we call the residual Pigouvian effect which accounts for the reduction in welfare in the polluting market due to a decrease in output and input use. Simulations conducted using data from Washington and Oregon indicate that the imposition of a revenue-neutral tax raises welfare by 19% to 20% and increases the cellulosic biofuel sector marginally at a rate of 1% to 2%. The residual Pigouvian effect accounts for 5% to 8% of welfare change. Also, increases in the input ratio requirement for cellulosic biofuel from the RFS will have little impact on the optimal revenue-neutral tax rate and corresponding welfare. However, changes to the cellulosic biofuel waiver price, which can be used to circumvent the input ratio requirement, reduces the optimal revenue-neutral tax because less pollution is emitted.

Keywords: Double-dividend, Renewable Fuel Standard, Carbon Tax
JEL Codes: H23, Q48, Q16, Q43

Introduction

A carbon tax has been touted by economists and environmental scientists as an effective and efficient means of reducing greenhouse gas (GHG) emissions (Tol 2005) but considerable opposition exists in the U.S. at the national level for adopting such a program. However, when the tax revenue from a carbon tax is used to offset an existing distortionary tax policy, public support across political groups increase drastically (Amdur et al. 2014). Representative John Delaney recently announced that he would introduce a federal legislature taxing GHG emissions and using the revenues to offset corporate tax rate (Congress John Delaney 2015). California, New York, Massachusetts, Oregon and Washington have proposed initiatives that imply a revenue-neutral carbon tax while reducing an existing distortionary tax. Thus, there is growing support to impose a revenue-neutral tax system to control GHG emissions at the state level.[1]

Even though the U.S. government has not implemented a federal law regulating GHG emissions, congress passed the Energy Independence and Security Act (EISA) of 2007 which imposes increasing consumption mandates designated as Renewable Fuel Standards (RFS) for several types of renewable fuel through 2022. The law is a way to reduce GHG emissions by substituting for energy feedstock that has a relatively lower emissions coefficient. The law indicates an increasingly important role for biofuels derived from cellulosic feedstocks. By 2022, the mandate calls for the consumption of approximately 16 billion gallons of cellulosic biofuel; a significant increase from 33 million gallons produced in 2014 (RFSP 2015). There are two important RFS policies relating to the cellulosic biofuel requirement: the input ratio requirement, which imposes a lower bound on the amount of cellulosic fuel used in production, and the price of waivers,

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[1] Outside of the U.S., a few countries have started experimenting with the use of revenue-neutral carbon taxes. The carbon tax implemented in the Canadian province of British Columbia in 2008 has reduced emissions by an estimated 5-15% with all tax revenues distributed back to consumers through offsetting tax reductions and transfers (Murray and Rivers, 2015). Several European countries have experimented with carbon taxes. For example, Norway implemented a carbon tax in 1991 with tax revenues redistributed to consumers through pension funds (Sumner, Bird, and Smith, 2009).

which can be used to circumvent the input requirement. Given the growing interest in establishing a revenue-neutral tax system controlling GHG emissions in several states, an interesting question arises: How will a revenue-neutral tax affect welfare in the presence of the RFS policies that incentivize cellulosic fuel production?

The objective of this article is to determine the effect on welfare and cellulosic fuel production from a revenue-neutral tax that reduces GHG emissions given the existing RFS policies related to the cellulosic biofuel requirements. We build a multi-sector general equilibrium model where a tax is placed on fossil fuel use and the tax revenue is used to offset a distortionary tax – either an income tax or a sales tax. This approach allows us to compare and contrast the effects of a revenue-neutral tax in states where state income tax is offset (such as Oregon) or when sales taxes are offset because state income taxes are zero (such as Washington). We focus our analysis on the consumption mandates specific to cellulosic biofuel due to its relative importance in EISA. We provide a numerical simulation based on data from Washington and Oregon, states that are significant providers of cellulosic feedstocks for biofuels due to their abundance of agricultural land and woody biomass (Yoder et al. 2010), and provide two contrasting sources of reduction in distortionary taxes.

This article makes theoretical and policy contributions. In the double dividend literature, three effects are identified when a revenue-neutral tax is imposed: a Pigouvian effect that improves welfare by reducing pollution damages, a revenue-recycling effect that reduces deadweight loss in a market with an existing distortionary tax and a tax interaction effect that reduces welfare because of a reduction in the existing tax base. In our theoretical model, we identify a fourth effect that we call the residual Pigouvian effect which is the reduction in welfare in the polluting market due to a decrease in output and input use. Such an effect occurs when a polluting input tax is imposed instead of a polluting output tax. Furthermore, an income tax has a larger marginal excess burden than a sales tax leading to a larger revenue-recycling and tax interaction effect in Oregon than Washington. We also show that more stringent input-ratio requirements and higher waver prices lead to lower revenue-neutral taxes because of a reduction in pollution. The effect of higher waiver prices on the revenue-neutral tax is much more elastic than the input-ratio requirement. The intuition is that in the presence of a waiver requirement, a high input ratio requirement would entice the firm to purchase more waivers instead leading to more pollution and continued need for higher taxes.

The double dividend hypothesis states that when an environmental tax is implemented, the economy yields two benefits. The first is a Pigouvian effect in the form of lower pollution and the second is a revenue-recycling effect in the form of lower deadweight loss in a market where a distortionary tax is decreased by the amount of pollution tax revenues raised (Pearce 1991).[2] A negative third effect called the tax interaction effect was identified where pollution taxes that raise the price of a dirty good relative to leisure price leads to less work and a lower income tax revenue (Bovenberg and de Mooij 1994). Subsequent research has shown that the Pigouvian and revenue-recycling effects are significant enough to offset the tax interaction effect leading to a positive environmental tax albeit lower than the Pigouvian level (Parry 1995). In the theoretical models that delineate the three welfare effects, the tax considered is on the output itself. In the context of gasoline production, a mix of fuel sources exists. In the U.S., ethanol is mixed with fossil fuel where the latter has a significantly higher emission coefficient. Thus, there is a need to explicitly model a revenue-neutral tax on a dirty input.

The renewable fuel mandate set by the EPA is a pollution standard based on the level of inputs. Such a pollution standard is second only to restrictions on the level of output in curbing total production of a dirty firm (Helfand 1991). The input-ratio mandate in cellulosic production is

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[2] Bovenberg and Goulder (2002) provides an extensive survey of the literature.

coupled with waiver credits (GPO 2011). These two instruments together have led to no significant effect on cellulosic production even when the input-ratio requirement is raised because firms have the option to purchase waivers instead (Skolrud et al. 2014). Cellulosic fuel production increases when waiver prices increase (Skolrud et al. 2014). We are not aware of any study that considers the welfare effects of a revenue-neutral tax in the presence of the RFS policies.

We modify the general equilibrium model developed by Goulder et al. (1997) to derive analytic expressions for the welfare effects from a revenue-neutral tax in the presence of the RFS policy. We build on their model by integrating imperfect competition, an input ratio mandate, the addition of intermediate sectors, and the possibility of recycling tax revenue into a consumer sales tax instead of a labor income tax. We show that when the pollution tax is on the input of production instead of output, a fourth effect emerges which reflects a further decline in output production in the dirty sector due to a reduction in input use. We also show that the addition of more intermediate sectors mainly add on to the tax interaction effect. Finally, the recycling of revenues to reduce sales tax instead of income tax leads to a change in the revenue recycling and tax interaction effect terms. The overall magnitude of both effects are dependent on the sensitivity of the tax base to changes in the price of the polluting good.

We turn to numerical simulation to provide clarity on general equilibrium effects. Results indicate that the imposition of a revenue-neutral tax would be welfare by 19% to 20% in Washington and Oregon, respectively. We find that the optimal revenue-neutral tax is approximately 72% of the optimal Pigouvian tax, which is typical based on estimates in the literature (Galinato and Yoder 2010; Parry 1995). We also find that the optimal tax rate is sensitive to changes in the price of waiver credits but not the input ratio mandate. Also, cellulosic biofuel usage increases with the revenue-neutral tax by 2% in Washington when revenues are used to offset sales tax and 1% in Oregon when revenues offset income tax.

Theoretical model

Our baseline general equilibrium model includes a consumption sector where a representative consumer purchases goods produced in two final goods sectors: a composite goods sector and a blended fuel sector that is directly affected by the RFS mandates. A government chooses the optimal tax instrument given the welfare of all agents in the economy. We assume that an income tax exists and it is the main beneficiary from the pollution tax revenue. Cellulosic feedstock is exogenous in the baseline model but we endogenize it in our extension.

Consumption sector

The consumer derives utility from blended fuel, *B*, the composite good, *X*, leisure, *H*, and environmental quality,

$$(1) \qquad U\left(B, X, H, E\right) = u\left(B, X, H\right) - c\left(E\right),$$

where E is total emissions, $u(\bullet)$ is increasing and concave in all the arguments and $c(\bullet)$ is an increasing convex function. Use of crude oil, Y^o, in the production of blended fuel leads to environmental damage, i.e. $E = E(Y^o)$, where $E_{Y^o} > 0$.[3] Total income is derived from labor earnings and government transfers. The budget constraint is,

$$(2) \qquad p^b B + X = \left(w - t^l\right)\left(T - H\right) + G,$$

where p^b is the price of blended fuel, w is the wage rate, t^l is the per-unit tax on labor, T is an exogenous time endowment so that $\left(T - H\right)$ is time devoted to labor, and G is a lump sum government transfer from all tax revenues. The price of the composite good is normalized to 1. The structure of the consumer's budget constraint plays an important role in the double-dividend result. The right-hand side of equation (2) is similar to the literature, but the left-hand side differs

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[3] Subscripts indicate a partial derivative such that $F_x = \partial F / \partial x$. and $F_{xx} = \partial^2 F / \partial x^2$.

in that the consumer does not pay for the tax on blended fuel directly.[4] This distinction is necessary as we consider the imposition of an input tax on production as opposed to an output tax.

The first-order conditions for an interior solution from the maximization of the consumer's utility function in (1) subject to the budget constraint in (2), taking environmental quality as given, are as follows:

$$
\begin{aligned}
&\frac{\partial \mathcal{L}}{\partial B} = -u_B + \lambda p^b = 0, \\
&\frac{\partial \mathcal{L}}{\partial X} = -u_X + \lambda = 0, \\
&\frac{\partial \mathcal{L}}{\partial H} = -u_H + \lambda\left(w - t^l\right) = 0, \\
&\frac{\partial \mathcal{L}}{\partial \lambda} = \left(1 - t^l\right)\left(T - H\right) + G - p^b B - X = 0,
\end{aligned}
\tag{3}
$$

where λ is the Lagrange multiplier for the budget constraint, and is interpreted as the marginal utility of income. After manipulation, the first three equations show that the marginal rate of substitution between goods are equal and the last equation is the budget constraint. The equations in (3) can be solved simultaneously with the budget constraint to yield the consumer's demand functions, defined by $B(p^b, w, t^l)$, $X(p^b, w, t^l)$, and $H(p^b, w, t^l)$. We define the sub-indirect utility function as $v(p^b, w, t^l) = u(B(p^b, w, t^l), X(p^b, w, t^l), H(p^b, w, t^l))$.

Composite good sector

The composite good is produced using constant returns to scale technology with labor as the only input, $X = L^x$. The first-order condition of the associated profit maximization problem fixes the wage at one, i.e. *w=1*.

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[4] See the right-hand side of Goulder et al. (1997, p. 711) equation (5) for example.

Blended fuel sector

The blended fuel output by firm *i* is based on the production function $Y_i^b(Y_i^c, Y_i^o, L_i^b)$ where Y_i^b is the production function for blended fuel, Y_i^c is cellulosic ethanol, Y_i^o is crude oil and L_i^b is labor used in the production of blended fuel.[5] Output is increasing and concave in all arguments. The production of cellulosic ethanol and crude oil are assumed exogenous in the base model. There are *n* firms in the sector constituting an oligopoly so that the output price is endogenous. We assume that the firm takes all input prices as exogenous. The firm maximizes profit by choosing input quantities to maximize the following expression,

$$(4) \qquad \pi_i = p^b\left(\sum_{i=1}^n Y_i^b\left(Y_i^c, Y_i^o, L_i^b\right), t^l\right) Y_i^b\left(Y_i^c, Y_i^o, L_i^b\right) - p^c Y_i^c - \left(p^o + t^o\right) Y_i^o - wL_i^b - W_i,$$

where $p^b(\bullet)$ is the inverse demand for blended fuel, p^c is the price of cellulosic ethanol, p^o is the price of crude oil, t^o is the per-unit tax on crude oil use, and W_i is the total expenditure on waiver credits. From the RFS, blenders are required to use an amount of cellulosic ethanol equal to the crude oil purchased multiplied by an exogenous percentage set by the EPA but firms can purchase waiver credits (GPO 2011),

$$(5) \qquad Z^c Y_i^o = Y_i^c + \frac{W_i}{g},$$

where Z^c is the cellulosic ethanol RFS percentage standard and g is the waiver credit price.[6]

The firm maximizes profit in equation (4) subject to (5) by choosing cellulosic ethanol, crude oil and labor yielding the following first-order conditions:[7]

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[5] We dropped the capital input in the production of blended fuel. We can do this without loss of generality as it will not affect the results specific to the double-dividend hypothesis since it is not a taxed input, and it does not interact with the consumption sector or any relevant constraints.

[6] The waiver credit price is set by the EPA as the higher value between $0.25 and the average annual wholesale price of gasoline per gallon minus $3 (GPO, 2011).

[7] To reduce notational clutter, we remove *i* subscripts when representing partial derivatives of firm-level variables, e.g. $Y^b_{Y^c} = \partial Y_i^b / \partial Y_i^c$.

$$
(6) \qquad \begin{aligned}
\pi_{Y^c} &= p^b_{Y^b} Y^b_{Y^c} Y^b_i + p^b Y^b_{Y^c} - p^c + g = 0, \\
\pi_{Y^o} &= p^b_{Y^b} Y^b_{Y^o} Y^b_i + p^b Y^b_{Y^o} - p^o - t^o - gZ^c = 0, \\
\pi_{L^b} &= p^b_{Y^b} Y^b_{L^b} Y^b_i + p^b Y^b_{L^b} - w = 0.
\end{aligned}
$$

Each equation shows the value of marginal product of each input equal to its marginal cost. For crude oil, marginal cost includes the tax and the input ratio requirement. For cellulosic ethanol, the value of marginal product includes the value of the waiver price. The first-order conditions in (6) can be solved to derive the uncompensated input demand functions, given by $Y_i^c(p^c, p^o, w, t^o, t^l, g, Z^c)$, $Y_i^o(p^c, p^o, t^o, t^l, g, Z^c)$, and $L_i^b(p^c, p^o, t^o, t^l, g, Z^c)$.

Equilibrium

The general equilibrium conditions that solve the model are derived using equations (3), (6), the market clearing wage, i.e. $w = 1$, market clearing condition for labor, i.e. $T = L^b + X + H$, demand for blended fuel equals its supply,

$$
(7) \qquad B\left(p^b, t^l\right) = Y^b\left(Y^c\left(t^o, t^l, g, Z^c\right), Y^o\left(t^o, t^l, g, Z^c\right), L^b\left(t^o, t^l, g, Z^c\right)\right);
$$

and the government budget constraint is met,

$$
(8) \qquad G = t^l\left(T - H\right) + t^o Y^o + W,
$$

where $t^l(T - H)$ is the labor tax collected from the consumer, and $t^o Y^o + W$ is the sum of the tax collected on crude oil use and cellulosic ethanol waiver credit expenditures.[8]

Note that the structure of the government's budget constraint in equation (7) is also an important driver of double-dividend results (Goulder et al. 1997). The notable difference in our setup is the inclusion of waiver credit expenditures as a source of revenue for the government. This

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[8] Un-subscripted variables from the blended fuel firm's problem represent the corresponding industry level quantity, e.g. $Y^o = \Sigma_{i=1}^n Y_i^o$.

will be important for the following scenario: suppose that an increase in the crude oil tax prompts a decrease in crude oil use, which will lead to a decrease in the total amount of cellulosic ethanol required in accordance with the RFS standard. All else equal, this leads to a decrease in total waiver credit expenditures, which will lower government revenue. To achieve a revenue-neutral change after modifying tax-levels, this decrease in government revenue will need to be accounted for elsewhere.

Revenue-neutral policy change

Using implicit demand functions from the consumer's problem and the equilibrium prices, we can write the indirect utility function as:

$$U\left(t^o,t^l,g,Z^c\right)=u\left(B\left(p^b,t^l\right),X\left(p^b,t^l\right),H\left(p^b,t^l\right)\right)-c\left[E\left(Y^o\left(t^o,t^l,Z^c,g\right)\right)\right], \tag{9}$$

where we note that p^b is the equilibrium price of blended fuel from equation (7) and it can be express as a function of the tax rates, i.e. $p^b = p^b(t^o,t^l,g,Z^c)$.

To assess the impact of a revenue-neutral policy change, where increases in the crude oil tax are offset by decreases in the distortionary labor tax, we totally differentiate (9), divide by the marginal change in the crude oil tax and simplify using the equilibrium conditions to derive:[9]

$$\begin{aligned}\frac{1}{\lambda}\frac{dU}{dt^o}=&\underbrace{\left(D\left(Y^o\right)-p^bY^b_{Y^o}\right)\left(-\frac{dY^o}{dt^o}\right)}_{\text{Pigouvian effect}}+\underbrace{p^b\left(Y^b_{Y^c}\frac{dY^c}{dt^o}+Y^b_{L^b}\frac{dL^b}{dt^o}\right)}_{\text{Residual Pigouvian effect}}\\&+\underbrace{M\left(Y^o+t^o\frac{dY^o}{dt^o}+\frac{dW}{dt^o}\right)}_{\text{Revenue-recyling effect}}-\underbrace{\left(\left(1+M\right)t^lH_{t^o}+\frac{dL^b}{dt^o}\right)}_{\text{Interaction effect}},\end{aligned} \tag{10}$$

where $D\left(Y^o\right)=(1/\lambda)c_EE_{Y^o}$ is the marginal environmental damage in dollar terms and $M\equiv t^lH_{t^l}/(T-H-t^lH_{t^l})$ is the marginal excess burden of taxation. The numerator of M repre-

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[9] See Appendix 1 for more detail.

sents the partial equilibrium welfare loss from an increase in the labor tax, and the denominator represents the partial equilibrium gain in government revenues resulting from the tax. We identify four welfare effects of the crude oil tax: a Pigouvian effect, a residual Pigouvian effect, a revenue-recycling effect and a tax interaction effect.

The Pigouvian effect is the combined change in marginal damages and marginal utility resulting from the impact of the crude oil change on blended fuel. As long as the marginal social benefit, $D(Y^o) - p^b Y^b_{Y^o}$, is positive, the Pigouvian effect will be positive. This is a slight departure from double-dividend models that consider environmental taxes assessed on the output, in which case the entire effect dY^b / dt^o would be included in the Pigouvian effect.[10]

The residual Pigouvian effect that we find only occurs with a pollution tax on input and not output. It consists of the change in marginal utility from a change in blended fuel production resulting from changes in cellulosic ethanol and labor. This effect represents the change in blended fuel output resulting from changes in the use of clean inputs. As long as the output effect dominates the substitution effect, so that the marginal effect of the crude oil tax rate on cellulosic fuel and labor are both negative, the residual Pigouvian effect will be negative. This is consistent with our expectations since an increase in the crude oil tax leads to lower use of all inputs in the blended fuel sector, leaving less blended fuel available for consumption.

The revenue-recycling effect represents the gain in efficiency from using the crude oil tax revenue to offset the labor tax which reduces deadweight loss in the labor market. One of the additions to the revenue-recycling effect compared to the literature is the change in revenue resulting from changes to the firm’s cellulosic waiver expenditures, i.e.

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[10] Refer to Parry (1995, pp. S-73-S-76) for an example of intermediate good taxation and the resulting Pigouvian effect.

(11) $$\frac{dW}{dt^o} = g\left(Z^c \frac{dY^o}{dt^o} - \frac{dY^c}{dt^o} \right).$$

The sign of dW / dt^o is negative if the marginal decrease in cellulosic ethanol is smaller than the weighted marginal decrease in crude oil as a result of a change to the crude oil tax. The decrease in waiver expenditures will reduce the amount of revenue available to the government, mitigating some of the positive impact of the revenue-recycling effect. The overall revenue-recycling effect is positive as long as the marginal revenue from the crude oil tax, $Y^o + t^o(dY^o / dt^o)$, is larger than the marginal loss from the decrease in waiver revenue, dW / dt^o.

The tax interaction effect consists of three components. When blended fuel and leisure are substitutes, an increase in the blended fuel price increases leisure, thereby decreasing labor. This decrease in labor reduces labor tax revenue, $t^l H_{t^o}$, and increases the deadweight loss, $t^l MH_{t^o}$. The third effect is the decrease in labor available to the blended fuel sector, dL^b / dt^o. When the crude oil tax increases and less blended fuel is available to the consumer, labor shifts from the blended fuel sector towards leisure and composite good producing labor. The overall tax interaction effect is negative.

Optimal tax derivation

The government's problem is to maximize the sum of consumer surplus, profits from the fuel blending and composite commodity sectors, tax revenues, and waiver credit expenditures, minus the disutility from pollution by optimally choosing a tax on crude oil,

(12) $$\Omega\left(t^o\right) = \max_{t^o} \delta\left(t^o\right) + n\pi_i^b\left(t^o\right) + \pi^x\left(t^o\right) + \tau\left(t^o\right) + nW_i - c\left(t^o\right),$$

where consumer surplus is $\delta(t^o) \equiv v(t^o) - p^b(t^o)b(t^o) - X(t^o) - (w - t^l)H$, total tax revenue is $\tau(t^o) \equiv nt^o Y_i^o + t^l(T - H)$ and profits in the composite sector are π^x. After manipulation of the first order condition, the Pigouvian tax is,

(13) $$\hat{t}^o = \underbrace{c_E E_{Y^o}}_{A} - \frac{1}{nY^o_{t^o}}\left\{\delta_{t^o} - \underbrace{t^l H_{t^o} + nW_{t^o}}_{B}\right\}.$$

The Pigouvian tax, $\hat{t}^o$, can be decomposed into three components. The first component, *A*, represents the marginal damages from crude oil pollution. In a partial equilibrium framework, *A* is the only component. In a general equilibrium framework, the optimal Pigouvian tax will also impact equilibrium prices, which leads to two other effects: the marginal effect of the crude oil tax on consumer surplus, δ_{t^o}, and the marginal effect on government revenue, *B*.

To calculate the optimal revenue-neutral tax, we allow the labor tax to be a function of the crude oil tax, so that the government's objective function is written as $\Omega = \Omega(t^o, t^l(t^o))$.Taking first order conditions and solving for the optimal revenue-neutral tax,

(14) $$\tilde{t}^o = \frac{1}{\gamma}\hat{t}^o - \frac{1}{n\tilde{Y}^o_{t^o}}\frac{dt^l}{dt^o}\Omega_{t^l},$$

where $\tilde{Y}^o_{t^o} \equiv Y^o_{t^o} + Y^o_{t^l}(dt^l / dt^o)$ is the marginal change in crude oil use from the crude oil tax under revenue-neutral taxation, $\gamma \equiv \tilde{Y}^o_{t^o} / Y^o_{t^o}$ is the ratio of marginal changes in crude oil use from the crude oil tax under revenue-neutral and Pigouvian taxation respectively, $\Omega_{t^l} \equiv \delta_{t^l} + nt^o Y^o_{t^l} + T - H - t^l H_{t^l} + nW_{t^l} - nc_E E_{Y^o} Y^o_{t^l}$ is the marginal impact on social welfare from the labor tax, and $dt^l / dt^o = -(Y^o + t^o(dY^o / dt^o) + dW / dt^o - t^l H_{p^b}(dp^o / dt^o)) / (T - H - t^l H_{t^l})$ is the reduction in income tax that can be financed by a change in crude oil tax while maintaining a balanced budget. The revenue-neutral tax is a fraction of the Pigouvian tax minus a term that captures the social welfare loss from labor taxation. We expect the optimal revenue-neutral tax to be lower than the Pigouvian tax. The difference in magnitude between the two taxes will depend on the difference between the change in crude oil as a result of the crude oil tax when the labor tax is variable $(\tilde{Y}^o_{t^o})$ and the change in the crude oil usage as a result of the crude oil tax when the labor tax is fixed $(Y^o_{t^o})$. The sign and magnitude of γ depends mainly on $Y^o_{t^l}(dt^l / dt^o),$ the marginal change in crude oil from a change in the labor tax multiplied by the reduction in the income tax that can be financed from crude oil tax revenues. For a complementary input relationship between labor and crude oil in the production of blended fuel, $Y^o_{t^l}(dt^l / dt^o) > 0,$ implying $\gamma > 1.$

Extending the baseline model

We extend the baseline model in two ways. First, we allow for the revenue from the crude oil tax to offset a sales tax instead of an income tax to examine how states without any income tax can benefit from a revenue-neutral tax. Second, we incorporate intermediate sectors in the production of cellulosic ethanol to endogenize the production process of cellulosic ethanol.

The double dividend with a sales tax

There are two distinct differences in the setup of the model with a sales tax instead of income tax. First, the budget constraint by the consumer now takes the form,

$$(15) \qquad p^b B + \left(1 + t^x\right) X = w\left(T - H\right) + G,$$

where t^x is the per-unit tax on the composite commodity. Notice that we have removed the labor tax from the right-hand side of the budget constraint. The second difference is the government's budget constraint which is now,

$$(16) \qquad G = t^x X + t^o Y^o + W.$$

Using a similar process as the baseline case, we can write the change in welfare given a change in crude oil tax based on our four effects as,[11]

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[11] See Appendix A.2 for proof.

$$\begin{aligned}\frac{1}{\lambda}\frac{dU}{dt^o} &= \underbrace{\left(D\left(Y^o\right) - p^b Y^b_{Y^o}\right)\left(-\frac{dY^o}{dt^o}\right)}_{\text{Pigouvian effect}} + \underbrace{p^b\left(Y^b_{Y^c}\frac{dY^c}{dt^o} + Y^b_{L^b}\frac{dL^b}{dt^o}\right)}_{\text{Residual Pigouvian effect}} \\ &\quad + \underbrace{M^x\left(Y^o + t^o\frac{dY^o}{dt^o} + \frac{dW}{dt^o}\right)}_{\text{Revenue-recyling effect}} - \underbrace{\left(\left(1 + M^x\right)t^x X_{t^o} + \frac{dL^b}{dt^o}\right)}_{\text{Interaction effect}}.\end{aligned} \tag{17}$$

where $M^x = -t^x X_{t^x} / (X + t^x X_{t^x})$ is the marginal excess burden of taxation from sales. The numerator of M^x is the loss composite good consumption to the consumer as a result of the tax, and the denominator is the marginal change in government revenue resulting from the tax. We find that differences in welfare effects between a sales or an income tax will hinge on marginal excess burden of taxation which in turn depends on the size of the tax base and the sensitivity of tax revenue to changes in the tax rate. If the marginal excess burden of taxation is larger for income tax, we expect that the absolute magnitudes of the revenue-recycling effect and tax interaction effects are larger compared to the sales tax case.

We use a similar government objective function as equation (12), with the exception of the tax revenue expression, which is now $\tau(t^o) = nt^oY^o + t^xX$, to derive the optimal Pigouvian tax,[12]

$$\hat{t}^{ox} = \underbrace{c_E E_{Y^o}}_{A} - \frac{1}{nY^o_{t^o}}\left\{\delta_{t^o} + \underbrace{t^x X_{t^o} + nW_{t^o}}_{B}\right\}. \tag{18}$$

The only major difference occurs in the *B* component, which is modified to allow for a marginal change in government revenue from the composite good tax rather than the labor tax.

Using a similar methodology as the baseline case, the optimal revenue-neutral tax, $\tilde{t}^{ox}$ is,

$$\tilde{t}^{ox} = \frac{1}{\gamma^x}\hat{t}^{ox} - \frac{1}{n\tilde{Y}^o_{t^o}}\frac{dt^x}{dt^o}\Omega_{t^x}, \tag{19}$$

where $\gamma^x \equiv (Y^o_{t^o} + Y^o_{t^x}(dt^x / dt^o)) / Y^o_{t^o}$ is the ratio of marginal changes in crude oil use from the

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[12] See Appendix A.3 for proof.

crude oil tax under revenue-neutral and Pigouvian taxation respectively, $dt^x / dt^o = -(Y^o + t^o(dY^o / dt^o) + dW / dt^o + t^x X_{t^o}) / (X + t^x X_{t^x})$ is the reduction in the sales tax that can be financed by a change in crude oil tax while maintaining a balanced budget, and $\Omega_{t^x} \equiv \delta_{t^x} + t^x X_{t^x} + X + nW_{t^x} - nc_E E_{Y^o} Y^o_{t^l} + nt^o Y^o_{t^x}$ is the marginal impact on social welfare from the sales tax. We expect the revenue-neutral tax to be lower than the Pigouvian tax.

Intermediate sectors in cellulosic fuel production

We derive the welfare effects when intermediate sectors in the production of cellulosic ethanol are included. Changes in the energy and consumption sectors resulting from the revenue-neutral tax and the ratio mandate will impact the intermediate sectors supplying the inputs to the fuel blending sector such as agriculture and forestry output used to produce cellulosic feedstock.

We simplify the production of cellulosic ethanol into two stages, cellulosic refining and cellulosic feedstock production. Production of cellulosic feedstock occurs in both the agricultural and forestry sectors. Capital (*K*), labor (*L*), and land (*R*) are inputs in each sector. Production in each sector is characterized by the production function $Y^s = Y^s(K^s, L^s, R^s), \forall s = a, f$, which is increasing and concave in all arguments. Assuming perfectly competitive markets, the equilibrium conditions for input use is such that the marginal product value of each input equals its price,

$$(20) \qquad p^s Y^s_{K^s}(K^s, L^s, R^s) - r = 0,$$

$$(21) \qquad p^s Y^s_{L^s}(K^s, L^s, R^s) - w = 0,$$

$$(22) \qquad p^s Y^s_{R^s}(K^s, L^s, R^s) - m = 0,$$

where p^s is the output price for $s = a, f$, *r* is the price of capital and *m* is the price of land.

Feedstock output from the agricultural and forest sectors is used along with capital and labor to produce cellulosic ethanol in the cellulosic refining sector. Production is determined by the function $Y^c = Y^c(K^c, L^c, Y^a, Y^f)$, which is also increasing and concave in all arguments. Assuming perfect competition and an output price p^c for cellulosic ethanol, we have the following first-order conditions:

(23) $$p^c Y^c_{K^c}(K^c, L^c, Y^a, Y^f) - r = 0,$$

(24) $$p^c Y^c_{L^c}(K^c, L^c, Y^a, Y^f) - w = 0,$$

(25) $$p^c Y^c_{Y^a}(K^c, L^c, Y^a, Y^f) - p^a = 0,$$

(26) $$p^c Y^c_{Y^f}(K^c, L^c, Y^a, Y^f) - p^f = 0,$$

where each condition equates the value of marginal product to its price.

Equilibrium entails that equations (20) through (26) hold along with the following market clearing conditions,

(27) $$Y^s(K^s, L^s, R^s) = Y^s(p^c, p^a, p^f, r, w),$$

$\forall s = a, f$, which equates cellulosic feedstock production to feedstock demand from the cellulosic refining sector,

(28) $$Y^c(K^c, L^c, Y^a, Y^f) = Y^c(p^b, p^c, p^o, t^o, w, r),$$

equating cellulosic ethanol production to ethanol demand from the blended fuel sector, and

(29) $$Y^b(p^b, p^c, p^o, t^o, w, r) = B(p^b, w, t^l),$$

which equates total blended fuel production to blended fuel demand from the consumer. Additionally, the markets for capital, land, and labor must also clear:

(30) $$\bar{K} = K^a + K^f + K^c + K^b,$$

(31) $$\overline{R} = R^a + R^f,$$

(32) $$T = L^a + L^f + L^c + L^b + L^x + H.$$

Conditions (27), (28), (30), and (31) are new, and equation (32) has been modified to allow for labor to be distributed to additional sectors.

As the arguments of the consumer's utility function do not change with the addition of the extra sectors with the exception of extra income from the capital endowment, the majority of the derivation of the double-dividend welfare effects remain the same,

(33) $$\frac{1}{\lambda}\frac{dU}{dt^o} = \underbrace{\left(D\left(Y^o\right) - p^b Y^b_{Y^o}\right)\left(-\frac{dY^o}{dt^o}\right)}_{\text{Pigouvian effect}} + \underbrace{p^b\left(Y^b_{Y^c}\frac{dY^c}{dt^o} + Y^b_{L^b}\frac{dL^b}{dt^o}\right)}_{\text{Residual Pigouvian effect}}$$
$$+ \underbrace{M\left(Y^o + t^o\frac{dY^o}{dt^o} + \frac{dW}{dt^o}\right)}_{\text{Revenue-recycling effect}} - \underbrace{\left(\left(1+M\right)t^l H_{t^o} + \frac{dL^b}{dt^o} + \frac{dL^a}{dt^o} + \frac{dL^f}{dt^o} + \frac{dL^c}{dt^o}\right)}_{\text{Interaction effect}}.$$

The first difference comes with the change in labor in the composite sector brought about by a change in the crude oil tax. With more sectors, there will be corresponding labor changes in each sector as total labor decreases with the substitute to leisure. The total effect of the labor decrease on welfare will be similar in each case, but in the case with more sectors, the change will simply be disaggregated to a finer degree in the tax interaction effect.

The second difference is the derivative expressions that comprise the economic welfare effects. In the baseline case, each of these derivatives could be determined by differentiation of the fuel blender's first-order conditions combined with the equilibrium blended fuel price equation. With more intermediate sectors, these derivatives will have to be determined using the full set of optimality conditions from each sector to account for the general equilibrium change.

Numerical simulation

To determine the effect of a revenue-neutral tax on cellulosic ethanol production in the agricultural and forestry sectors, we simulate the model for Washington State and Oregon. This allows us to contrast revenue-recycling of environmental tax with income tax (for Oregon) versus sales tax (for Washington). We calibrate the baseline model with imperfect competition extended to include the intermediate sectors.[13]

Functional forms and parameters

Constant elasticity of substitution (CES) production functions are employed in each sector because it is less restrictive and more tractable than a fully-flexible functional form such as the translog. Also, its popularity in calibration studies of environmental economics ensures a high degree of comparability across studies. In the agricultural, and forestry sectors, this implies that

$$(34)\qquad Y^s = A^s\left(d_K^s(K^s)^{\rho^s} + d_L^s(L^s)^{\rho^s} + d_R^s(R^s)^{\rho^s}\right)^{1/\rho^s},$$

for $s=\{a,f\}$, where A^s is a calibrated scaling/technology parameter, and d_K^s, d_L^s, and d_R^s are calibrated share parameters such that $d_K^s + d_L^s + d_R^s = 1$. The elasticity of substitution is defined by $\sigma^s \equiv 1/(1-\rho^s)$. The production technology for the cellulosic feedstock refining and blended fuel sectors, respectively, are:

$$(35)\qquad Y^c = A^c\left(d_K^c(K^c)^{\rho^c} + d_L^c(L^c)^{\rho^c} + d_{Y^a}^c(Y^a)^{\rho^c} + d_{Y^f}^c(Y^f)^{\rho^c}\right)^{1/\rho^c},$$

$$(36)\qquad Y^b = A^b\left(d_K^b(K^b)^{\rho^b} + d_L^b(L^b)^{\rho^b} + d_{Y^c}^b(Y^c)^{\rho^b} + d_{Y^o}^b(Y^o)^{\rho^b}\right)^{1/\rho^b}.$$

Finally, the utility function is CES as well, such that $u(B,X,H) = (d_B B^\rho + d_X X^\rho + d_H H^\rho)^{1/\rho}$.

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[13] Each sector of the model is calibrated such that each respective set of first-order conditions holds at the baseline data levels.

The share parameters of the utility function and each production function are calibrated and the elasticities of substitution come from the literature, which are shown in Table 1.

To calibrate the individual share parameters of the production functions, we use the method outlined by Howitt (1995). After applying the CES functional form selection to the production functions in each sector, the corresponding systems of first-order conditions are solved for production-share parameters as a function of data.[14]

The data used in these simulations is derived from different sources. We obtain quantity and price data for Washington and Oregon for various sectors and summarize their values and sources in Table 2. Differences in state-level quantities demonstrate Washington State's emphasis on agriculture over forestry, whereas Oregon is the opposite. Washington State employs more labor and capital in agriculture and less labor and capital in forestry than Oregon. Washington State has a higher wage rate and land rental rate than Oregon. The remainder of the prices in the model do not vary by state.

In 2014, the EPA reported national production of cellulosic ethanol equal to 33 million gallons (RFSP 2015). As state-level production is not provided, we assume that Washington State and Oregon accounted for a share of national cellulosic ethanol production equal to their respective shares of national petroleum consumption. In 2012, Washington's share of national petroleum consumption was 2% (EIA 2013d), while Oregon's share was 0.9% (EIA 2013e), accounting for cellulosic ethanol production of 660,000 gallons and 297,000 gallons, respectively.

In our model, we disaggregate the production of cellulosic feedstock into two sources, agriculture and forestry. Without information specifying production from each sector, we assume that half the feedstock is produced by the agricultural sector (in the form of switchgrass) and half

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[14] This method highlights the value of using the CES functional form: the system of first-order conditions in each sector is sufficient to uniquely identify all parameters of the production function (Howitt, 1995).

from the forestry sector. Using yield data from Sims et al. (2010), we calculate the amount of forest residues and switchgrass required to produce the postulated amount of cellulosic ethanol per state.[15] To calculate the forestry land requirement, we multiply forest residues (dry tons) by the ratio of state-level forestry land to state-level residue production (Gale et al. 2012; Smith, 2012). The agricultural land requirement is based on an estimated yield of 6 dry tons of switchgrass per acre (University of Kentucky 2013). We assume capital/land and labor/land ratios are the same as in state-level agriculture and forestry production.

Simulation results

With the calibrated parameters held fixed, we vary the values of three policy variables: the per unit tax on crude oil, the RFS percentage mandate, and the waiver price. We consider three different levels for the crude oil tax: zero, the optimal Pigouvian level, and the revenue neutral tax level. Values for the RFS percentage mandate are varied from their 2014 level through the proposed level in 2022. Finally, we consider waiver prices ranging from a baseline level of \$0.78/credit to \$2.23/credit in five-cent increments. In addition to examining the response of endogenous variables to changes in policy parameters, we examine changes to welfare effects.[16]

Table 3 summarizes our results, where the welfare effects are expressed in terms of dollars per gallon of crude oil. We find that the revenue-recycling and Pigouvian effects are positive, while the residual Pigouvian and interaction effects are negative as expected from our theory. The revenue-recycling effect is larger in Oregon than in Washington State. Therefore, simulation results suggest that the gain in efficiency from revenue-neutral taxation through the reduction of

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[15] Sims et al. (2010) indicate a range of 110 to 270 liters per ton (l/t) for conversion from agricultural material (switchgrass) to ethanol, and a range of 125 to 300 l/t for forestry residues. We use the midpoints of each range for our conversion factor.

[16] Each of these welfare effects is composed of derivatives whose value is estimated using the entire system of 25 optimality and market-clearing conditions through the multi-equation implicit function theorem. Each derivative expression is re-evaluated with the new endogenous prices and quantities at every step of the estimation.

deadweight loss is *higher* in the economy with an income tax as opposed to a sales tax. Similarly, the absolute value of the tax interaction effect is larger with an income tax from Oregon than a sales tax from Washington. These magnitudes are consistent with the fact that the marginal excess burden of taxation is larger for an income tax than for a sales tax (Ballard, Shoven, and Whalley 1985). The residual Pigouvian effect is smaller in magnitude compared to the other welfare effects but accounts for 5% to 8% of welfare change. A small negative residual Pigouvian effect indicates that the output effects slightly dominates substitution effects.

Approximately 2.6 billion gallons of fuel are consumed in Washington and 1.17 billion gallons in Oregon annually. Imposing a revenue-neutral tax yields $261 million and $164 million in annual welfare gains for Washington and Oregon, respectively. We calculate the percentage change from the no-tax baseline to the Pigouvian and revenue-neutral tax cases. We find welfare improvements in Washington State on the order of 11% from Pigouvian taxation and 19% from revenue neutral taxation. Oregon welfare improvements are 13% and 20% for Pigouvian and revenue neutral taxation, respectively. These results are similar to those of Goulder, Parry, and Burtraw (1997) who find net welfare gains between $153.7 million and $952.1 million dollars depending on the marginal damage of pollution. Under Pigouvian taxation, the authors find that welfare is between -121.1% and 36% of the double-dividend welfare level.

Next we examine values of the two taxes for each state as shown in Table 4. For Washington State, we use the Pigouvian and revenue-neutral tax expressions associated with a distortionary tax on the composite good (equations (18) and (19), respectively), and for Oregon, we use tax expressions associated with a distortionary tax on labor income (equations (13) and (14), respectively). Our results indicate that the revenue-neutral tax is approximately 68% to 73% of the Pigouvian tax due to the tax interaction effect and the residual Pigouvian effect. The results are consistent with evidence from Parry (1995) and Galinato and Yoder (2010). We also note that the Pigouvian tax is slightly higher than the marginal environmental damage ($0.25/gal. of crude oil) which is the result of a Pigouvian tax in a general equilibrium framework.

Imposition of either the Pigouvian or revenue-neutral tax regimes result in a notable change in both blended fuel and cellulosic fuel production as shown in Table 5. In general, both taxes lead to a decrease in blended fuel production and an increase in cellulosic fuel production. With the revenue-neutral tax, the absolute value of the change for each fuel type is slightly lower but doing so not only leads to a reduction in pollution but an increase in cellulosic fuel production by 1% to 2%. The results demonstrate that the firm substitutes away from the now expensive crude oil towards blended fuel, but that the substitution effect is not large enough to overcome the drop in total output of blended fuel from the output effect.

We simulate the tax response to an increase in the cellulosic waiver price (from $0.78/gallon to $2.23/gallon) and an increase in the cellulosic percentage standard based on the RFS schedule. Figures 1 and 2 illustrate the results for the Pigouvian tax and Figures 3 and 4 show the results for the revenue-neutral tax. The simulations indicate that each tax is much more sensitive to changes in the waiver price than to changes in the cellulosic percentage standard. In the Pigouvian tax case, the average elasticity measuring its responsiveness to the waiver price is -0.48 for Washington State and -0.47 for Oregon, whereas the responsiveness to the percentage standard is just -0.006 and -0.005 for Washington State and Oregon respectively. In the revenue-neutral tax case, responsiveness to the waiver price is -0.71 and -0.57, and responsiveness to the percentage standard is -0.009 and -0.008 for Washington State and Oregon, respectively. When the waiver price increases, producers use more cellulosic fuel, decreasing crude oil use and subsequent marginal environmental damage, necessitating a lower tax. When the percentage standard shifts, producers can mitigate its effect by purchasing cheap waiver credits, requiring insignificant changes to input levels. The level of marginal environmental damage is maintained along with the environmental tax.

We note further that the trend seen in Figures 1-4 is consistent across states, specifically, the slope of each curve varies only slightly. Interestingly, a consistent pattern for Washington State emerges even with its use of a retail sales tax in lieu of income taxes. This implies that the change in the optimal tax rate due to the change in government policy variables is relatively unaffected by the difference in tax structure.

In Figure 5 and Figure 6, we explore the impact of changes to the waiver price and RFS on cellulosic ethanol production. Cellulosic ethanol production responds to changes in the waiver price much more significantly compared to changes in the RFS. The impact on ethanol production from changes in the percentage standard is negligible because of the ability of producers to purchase waiver credits (Figure 6).

Figure 7 and Figure 8 examine changes in welfare from a revenue-neutral tax. Notice that the effect diminishes as waiver price increases (Figure 7) and RFS increases (Figure 8). Here, a high waiver price leads to more cellulosic ethanol use by the energy sector and lower emissions. Thus, emission taxation has a correspondingly smaller impact on welfare. All four effects decrease in absolute value over the range of waiver price and RFS percentages considered, but the positive effects decrease at a faster rate than the negative effects, yielding a decreasing effect of the influence of the crude oil tax on welfare. Also, since more stringent RFS mandates can be met with more waiver purchases, the change in welfare given this instrument is not declining as fast as the waiver price change because the level of pollution remains steady.

Conclusion

This article analyzes the welfare implications of imposing a revenue-neutral tax in the context of the Renewable Fuel Standard (RFS). We formulate a multi-sector general equilibrium model that includes a fuel production sector that is subject to both RFS requirements and a revenue-neutral tax on fossil fuel (crude oil) usage, and a consumer sector that values consumption of blended fuel and environmental quality. The model admits analytical components relating to the double-dividend hypothesis, plus a new component, the residual Pigouvian effect, which arises when the environmental tax is assessed on the input of a dirty producer instead of the output.

We show theoretically that tax revenues can be recycled into a non-labor tax and still have welfare enhancing effects, provided that the substitutability between fuel and the taxed good does not allow for a tax interaction effect that exceeds the revenue-recycling effect. We extend the basic model to include imperfect competition and intermediate sectors for the energy sector.

We find simulated values for the revenue-neutral tax consistent with other estimates in the literature. We present evidence that the RFS waiver credit price can impact the optimal tax rate, while the RFS percentage standard for cellulosic biofuel has only a limited effect. With a suitable increase in the price of cellulosic waiver credits, cellulosic ethanol production has the potential to increase substantially. However, large changes to the RFS percentage standard will have limited effect on production if the waiver price is low. This result echoes previous research highlighting the danger to the burgeoning cellulosic ethanol industry from incorrectly priced waiver credits. Finally, we note that an increase in the waiver price will *decrease* the welfare impact of revenue-neutral taxation. This is likely due to lower emissions resulting from higher waiver prices leading to the use of more cellulosic ethanol.

Our results imply that by imposing a revenue-neutral tax on fossil fuel usage in fuel production, social welfare increases in the form of lower pollution and higher cellulosic production. They also imply that with an appropriately high waiver credit price, the optimal tax rate could be reduced substantially while still yielding the same societal benefits.

References

Amdur, D., B. Rabe and C. Borick. 2014. Public Views on a Carbon Tax Depend on the Proposed Use of Revenue. *Issues in Energy and Environmental Policy* 13.

Bairam, E. 1991. Elasticity of Substitution, Technical Progress and Returns to Scale in Branches of Soviet Industry: a new CES production function approach. *Journal of Applied Econometrics* 6, 91-96.

Ballard, C. L., Shoven, J. B., and J. Whalley. 1985. General Equilibrium Computations of the Marginal Welfare Costs of Taxes in the United States. *American Economic Review* 75 (1): 128-138.

Banks J., Blundell, R., and A. Lewbel. 1997. Quadratic Engel Curves and Consumer Demand. *The Review of Economics and Statistics* 79 (4), 527-539.

BLS (U.S. Bureau of Labor Statistics). 2013a. May 2012 State Occupational Employment and Wage Estimates: Washington State. Available at: http://www.bls.gov/oes/current/oes_wa.htm#45-0000 (accessed September 2013).

BLS (U.S. Bureau of Labor Statistics). 2013b. May 2012 State Occupational Employment and Wage Estimates: Oregon. Available at: http://www.bls.gov/oes/current/oes_or.htm#45-0000 (accessed September 2013).

Bovenberg, A.L. and R.A. de Mooij. 1994. Environmental Levies and Distortionary Taxation. *American Economic Review*, 94 (4), 1085–89.

Bovenberg, A. L. and L.H. Goulder. 2002. Environmental Taxation and Regulation. *Handbook of Public Economics*, in: A. J. Auerbach & M. Feldstein (ed.), Handbook of Public Economics, Edition 1, Volume 3, Chapter 23, Pages 1471-1545

Congress John Delaney. 2015. Delaney Announces Climate Change Legislation to Reduce Carbon Pollution, Protect Middle Class, Boost Economic Growth. Press Release. Available at: http://delaney.house.gov/news/press-releases/delaney-announces-climate-change-legislation-to-reduce-carbon-pollution-protect

Daniels, J.M. 2010. Assessing the Lumber Manufacturing Sector in Western Washington. *Forest Policy and Economics* 12, 129-135.

EIA (U.S. Energy Information Administration). 2013a. Spot Prices for Crude Oil and Petroleum Products. Available at: http://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm (accessed September 2013).

——. 2013b. West Coast Less California Gasoline and Diesel Retail Prices. Available at: http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_r5xca_a.htm (accessed September 2013).

——. 2013c. Washington State Profile and Energy Estimates: Profile Analysis. Available at: http://www.eia.gov/state/?sid=WA (accessed December 2013).

——. 2013d. Oregon Profile and Energy Estimates: Profile Analysis. Available at: http://www.eia.gov/state/?sid=OR (accessed December 2013).

ERS (USDA Economic Research Service). 2014. National Tables, 1948-2011, Tractor Rental Rate. Available at: http://www.ers.usda.gov/data-products/agricultural-productivity-in-the-us.aspx (accessed February 2014).

Gale, C.B., Keegan III, C.E., Berg, E., Daniels, J., Christensen, G.A., Sorenson, C.B., Morgan, T.A., Polzin, P. 2012. Oregon's Forest Products Industry and Timber Harvest, 2008: Industry Trends and Impacts of the Great Recession through 2010. USDA General Technical Report PNW-GTR-868.

Galinato, G. I., and J. K. Yoder. 2010. An Integrated Tax-Subsidy Policy for Carbon Emission Reduction. *Resource and Energy Economics* 32: 310-326.

Goulder, L. H., Ian W. H. Parry, and D. Burtraw. 1997. Revenue-Raising versus Other Approaches to Environmental Protection: The Critical Significance of Preexisting Tax Distortions. *The RAND Journal of Economics* 28 (4): pp. 708-731.

Governors' Biofuel Coalition (GBC). 2011. Cellulosic Ethanol Won't Reach First-Generation Price Until 2020 — Study. Available at: http://www.governorsbiofuelscoalition.org/?p=679 (accessed September 2013).

GPO (Government Printing Office). 2011. Code of Federal Regulations,Title 40, Part 80.1456. Available at: http://www.gpo.gov/fdsys/browse/collectionCfr.action?collectionCode=CFR (accessed October 2014).

Helfand, G.E., 1991. Standards versus standards: the effects of different pollution restrictions. The American Economic Review 81, 622-634.

Howitt, R. E. 1995. A Calibration Method for Agricultural Economic Production Models. *Journal of Agricultural Economics* 46: 147-159.

Murray, B. C. and N. Rivers. 2015. British Columbia's Revenue-Neutral Carbon Tax: A Review of the Latest 'Grand Experiment' in Environmental Policy. NI WP 15-04. Durham, NC: Duke University. http://nicholasinstitute.duke.edu/publications.

NASS (USDA National Agricultural Statistics Service). 2013a. Quick Stats: Rent, Cash, Cropland-Expense. Available at: http://quickstats.nass.usda.gov/results/95303089-CE93-3EED-9B56-68C096A8B8CB (accessed September 2013).

——. 2013b. Quick Stats: Tractors-Inventory. Available at: http://quickstats.nass.usda.gov/results/3EE349F8-6DF1-30C4-BCA0-C67A886F25A8 (accessed September 2013).

——. 2013c. Quick Stats: Area Cropland, Harvested. Available at: http://quickstats.nass.usda.gov/results/93F20082-8A27-3E48-9524-37A2749EE556 (accessed September 2013).

——. 2013d. Crop Values: 2012 Summary. Available at: http://usda.mannlib.cornell.edu/usda/nass/CropValuSu//2010s/2012/CropValuSu-02-16-2012.pdf (accessed September 2013).

Parry, I. W. H. 1995. Pollution Taxes and Revenue-recycling . *Journal of Environmental Economics and Management* 29 (3): S64 - S77.

Pearce D.W 1991. The role of carbon taxes in adjusting to global warming. *Economic Journal*, 101: 938-948.

Renewable Fuel Standard Program (RFSP): Standards for 2014, 2015, and 2016 and Biomass-Based Diesel Volume for 2017, 80 Fed. Reg. No. 111 (Jun. 10, 2015) (amending 40 CFR pt. 80).

Sims, R. E. H., W. Mabee, J. N. Saddler, and M. Taylor. 2010. An Overview of Second Generation Biofuel Technologies. *Bioresource Technology* 101: 1570-1580.

Skolrud, T. D., G. I. Galinato, S. P. Galinato, C. R. Shumway, and J. K. Yoder. 2014. The Role of Market Structure and Federal Renewable Fuel Standards in the Growth of the Cellulosic Biofuel Sector. *School of Economic Sciences Working Paper Series* WP 2014-2: 1-41.

Smith, D. 2012. Washington Mill Survey 2010: Series Report #21. Washington State Department of Natural Resources. Available at: http://www.dnr.wa.gov/Publications/obe_econ_rprt_millsurv_2010.pdf (accessed September 2013).

Sumner, J., L. Bird, and H. Smith. 2009. Carbon Taxes: A Review of Experience and Policy Design Considerations. National Renewable Energy Laboratory Technical Report: NREL/TP-6A2-47312.

Tol, R.S.J., 2005. The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. Energy Policy 33(16), 2064-2074.

University of Kentucky. 2013. Switchgrass for Bioenergy. University of Kentucky College of Agriculture Cooperative Extension Service. Available at: https://www.uky.edu/Ag/CDBREC/introsheets/switchgrass.pdf (accessed September 2013).

Washington Research Council (WRC). 2012. The Economic Contribution of Washington State's Petroleum Refining Industry in 2011. *Economic Profile*. Available at: https://researchcouncil.files.wordpress.com/2013/08/2012refineryreportfinal040913.pdf (accessed March 2015).

Yoder, J. K., C. R. Shumway, P. Wandschneider, D. Young, H. H. Chouinard, A. Espinola-Arredondo, S. P. Galinato, et al. 2010. Biofuel Economics and Policy for Washington State. Tech. rep., Washington State University Agricultural Research Center Research Bulletin. http://cru.cahe.wsu.edu/CEPublications/XB1047E/XB1047E.pdf

Tables

TABLE 1—ELASTICITIES OF SUBSTITUTION

Sector	Elasticity	Source
Agricultural sector[a]	0.21	Yi et al. (2014)
Forestry sector[b]	0.46	Daniels (2010)
Cellulosic refining sector	2.00	Assumption
Blended fuel sector	0.85	Bairam (1991)
Composite good sector	2.00	Assumption
Consumer's utility function	0.1068	Banks et al. (1997)

[a] We use estimates from switchgrass production for the agricultural sector.

[b] The elasticity is an average of three different estimated elasticities between capital and labor, labor and logs, and capital and logs.

TABLE 2—PARAMETER VALUES

Parameters	Value		Units	Source
	WA	OR		
Inputs:				
Agricultural labor[a]	1.16	0.34	Index	BLS (2013)
Agricultural capital[b]	16.68	6.52	Index	NASS (2013b)
Agricultural resources	1,096	493	Acres	Computed
Forestry labor[c]	3.17	1.87	Index	BLS (2013)
Forestry capital[d]	0.05	0.06	Index	Smith (2012)
Forestry resources	17,257	11,840	Acres	Computed
Cellulosic refining labor	1130	200	Index	BLS (2013)
Cellulosic refining capital	50	116	Index	Smith (2012)
Fuel blending labor[e]	1130	1130	Workers	BLS (2013)
Fuel blending capital[f]	148,712	148,712	$ (th.)	WRC (2012)
Crude oil	5.6	2.5	Gallons (bil.)	EIA (2013d)
Composite good labor	15,035	12,098	Index	BLS (2013)
Composite good capital	174,157	159,495	Index	NASS (2013b), Smith (2012)
Composite good resources	27.6	36.6	Acres (mil.)	NASS (2013c), Smith (2012)
Outputs:				
Cellulosic feedstock, agriculture	6,575	2,959	Tons	Computed (Sims et al. 2010)
Cellulosic feedstock, forestry	5,879	2,645	Tons	Computed (Sims et al. 2010)
Cellulosic ethanol	660	297	Gallons (th.)	Computed (RFSP, 2015)
Blended fuel	2.60	1.17	Gallons (bil.)	EIA (2013d; 2013e)
Composite good	10.7	5.96	Index	NASS (2013d), Gale et al. (2012), Smith (2012)
Prices:				
Wage rate	36,296	33,596	$/year	BLS (2013a; 2013b)
Rental rate of capital	0.1819	0.1819	Index	ERS (2014)
Land resource price	215	130	$/acre	NASS (2013a)
Cellulosic feedstock, agriculture	65	65	$/dry ton	U. Kentucky (2013)
Cellulosic feedstock, forestry	52.27	52.27	$/dry ton	Gale et al. (2012)
Cellulosic ethanol	2.35	2.35	$/gallon	GBC (2011)
Crude oil	2.24	2.24	$/gallon	EIA (2013b)
Final blended fuel[g]	3.76	3.76	$/gallon	EIA (2013c)

[a] The input quantity of labor consists of agricultural inspectors, graders and sorters of agricultural products, agricultural equipment operators, and general farmworkers.

[b] Agricultural capital is computed as an index based on the amount of agricultural equipment (tractors) available in Washington State in 2012 (NASS, 2013b).

[c] Labor input in the forestry sector consists of forest and conservation workers, fallers, logging equipment operators, and log graders and scalers.

[d] We computed an index of forestry capital based on the number of sawmills (Smith, 2012).

[e] Labor for the blended fuel sector includes categories for petroleum pump system operators, refinery operators and gaugers.

[f] Total 2012 non-labor capital expenditures.

[g] The final blended fuel price is the 2012 average retail gasoline price for the Western United States less California (EIA, 2013c).

TABLE 3—WELFARE EFFECTS

Welfare effects ($/gal. of crude oil)	State WA	 OR
Revenue-recycling	$0.16	$0.20
Pigouvian	$0.13	$0.16
Residual Pigouvian	-$0.04	-$0.03
Interaction	-$0.15	-$0.19
Sum of effects	$0.10	$0.14
Aggregate social welfare effects (percentage increase in social welfare from no-tax baseline)	WA	OR
Pigouvian taxation	11%	13%
Revenue neutral taxation	19%	20%

TABLE 4—OPTIMAL TAXES AT BASELINE PARAMETER VALUES ($/GAL. OF CRUDE OIL)

	State	
	WA	OR
Pigouvian	$0.26	$0.31
Revenue neutral	$0.19	$0.21

TABLE 5—CHANGE IN FUEL PRODUCTION (MILLIONS OF GALLONS)

	State	
	WA	OR
2012 Baseline values		
Blended fuel	2604.11	1171.85
Cellulosic fuel	0.66	0.30
With Pigouvian Tax (% change from baseline)		
Blended fuel	-6.89%	-3.81%
Cellulosic fuel	3.01%	1.10%
With Revenue Neutral Tax (% change from baseline)		
Blended fuel	-5.14%	-3.04%
Cellulosic fuel	1.53%	0.61%

Figures

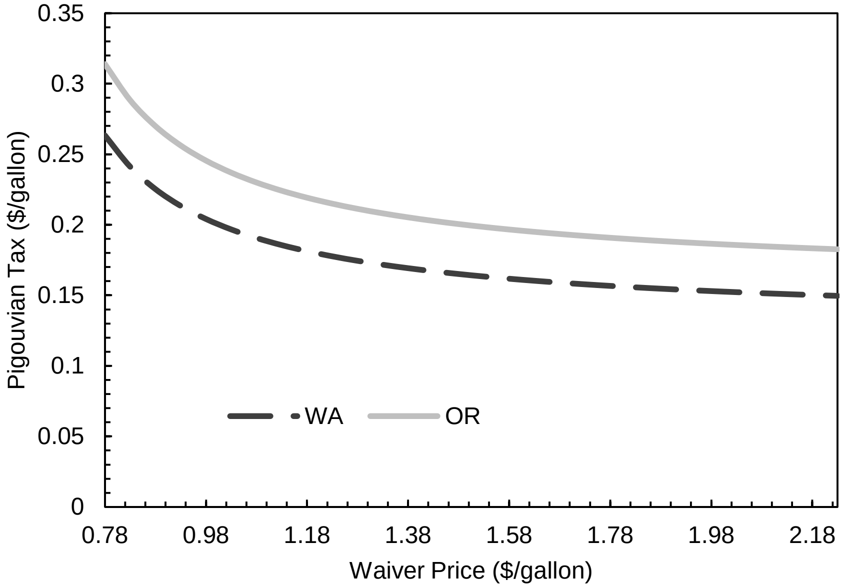

FIGURE 1. SIMULATED RESPONSE OF THE PIGOUVIAN TAX TO CHANGES IN THE WAIVER PRICE

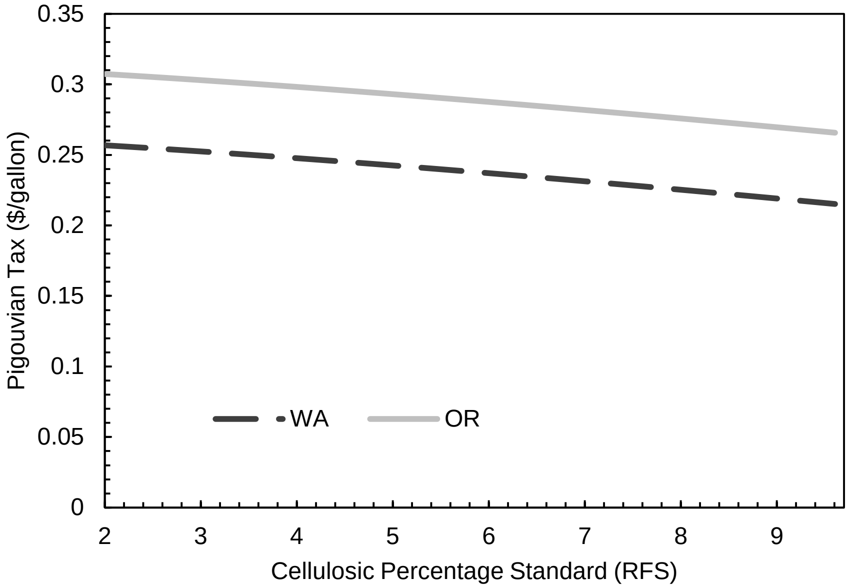

FIGURE 2. SIMULATED RESPONSE OF THE PIGOUVIAN TAX TO CHANGES IN THE RFS

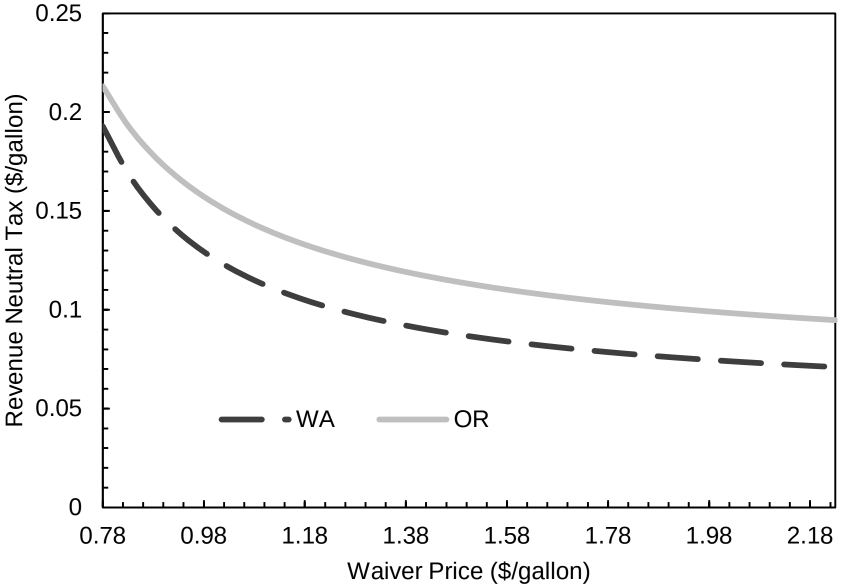

FIGURE 3. SIMULATED RESPONSE OF THE REVENUE NEUTRAL TAX TO CHANGES IN THE WAIVER PRICE

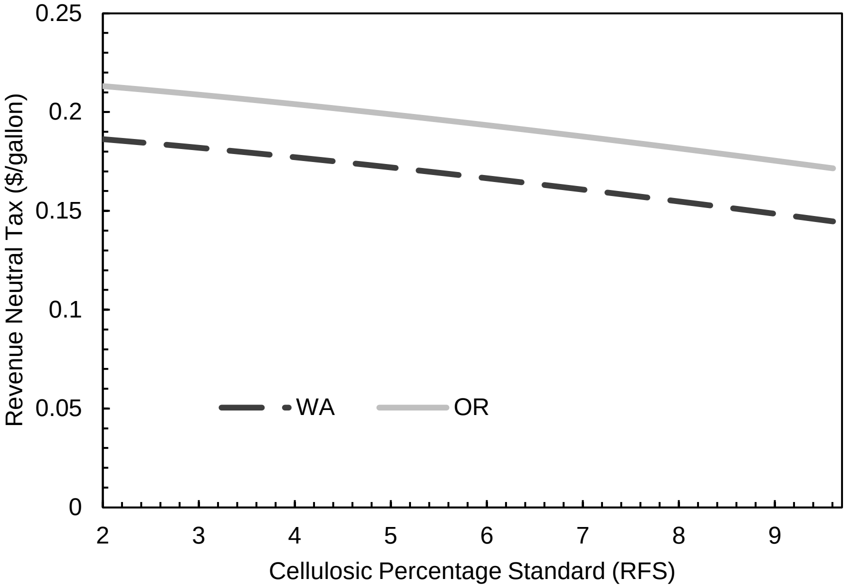

FIGURE 4. SIMULATED RESPONSE OF THE REVENUE NEUTRAL TAX TO CHANGES IN THE RFS

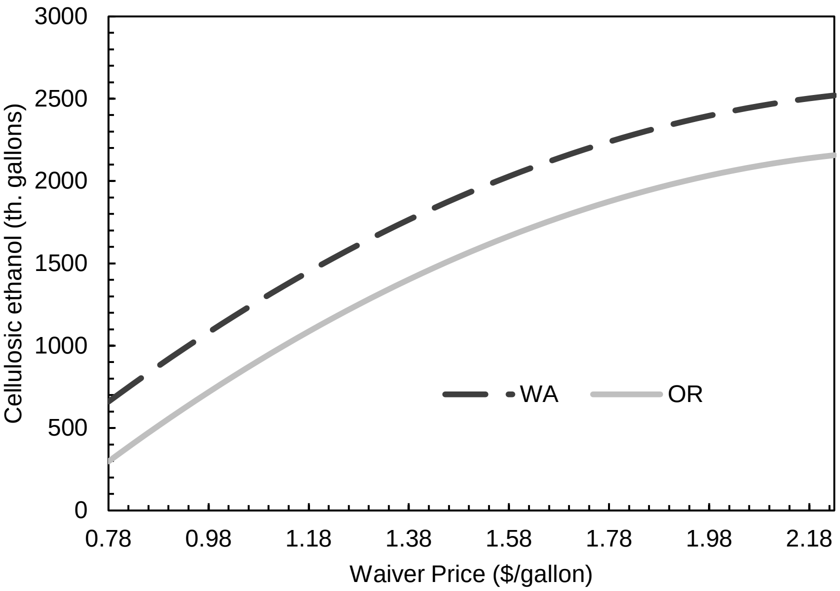

FIGURE 5. SIMULATED RESPONSE OF CELLULOSIC ETHANOL PRODUCTION TO CHANGES IN THE WAIVER PRICE

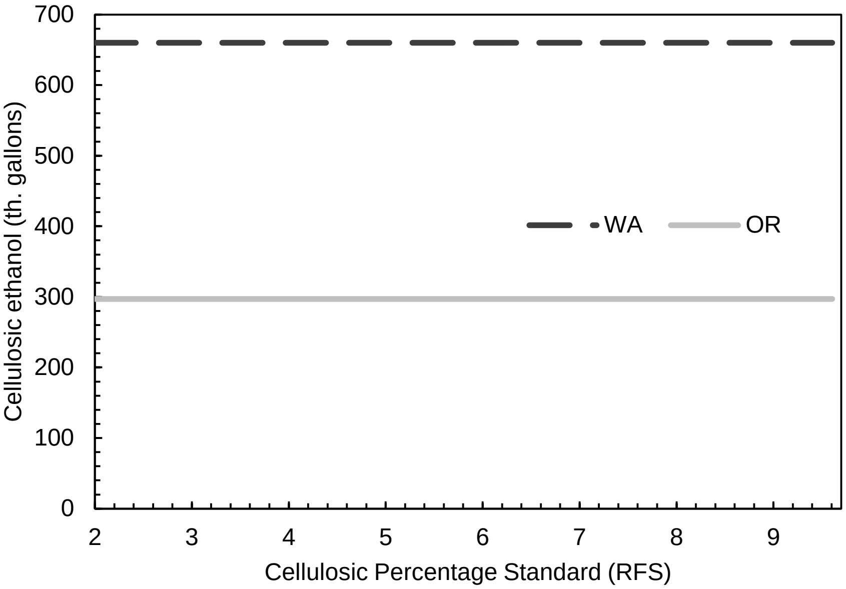

FIGURE 6. SIMULATED RESPONSE OF CELLULOSIC ETHANOL PRODUCTION TO CHANGES IN THE RFS

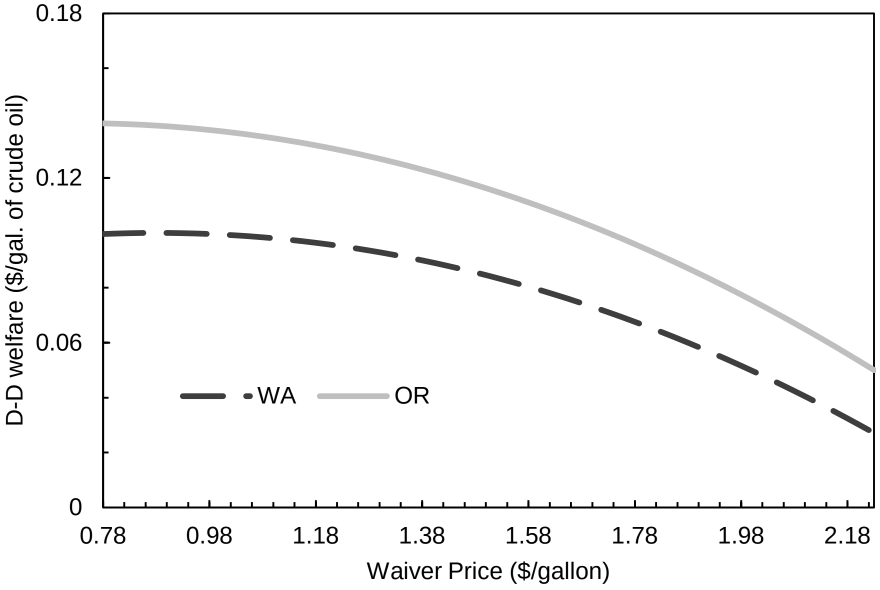

FIGURE 7. SIMULATED RESPONSE OF DOUBLE-DIVIDEND WELFARE (PER $/GAL. OF CRUDE OIL) TO CHANGES IN THE WAIVER PRICE

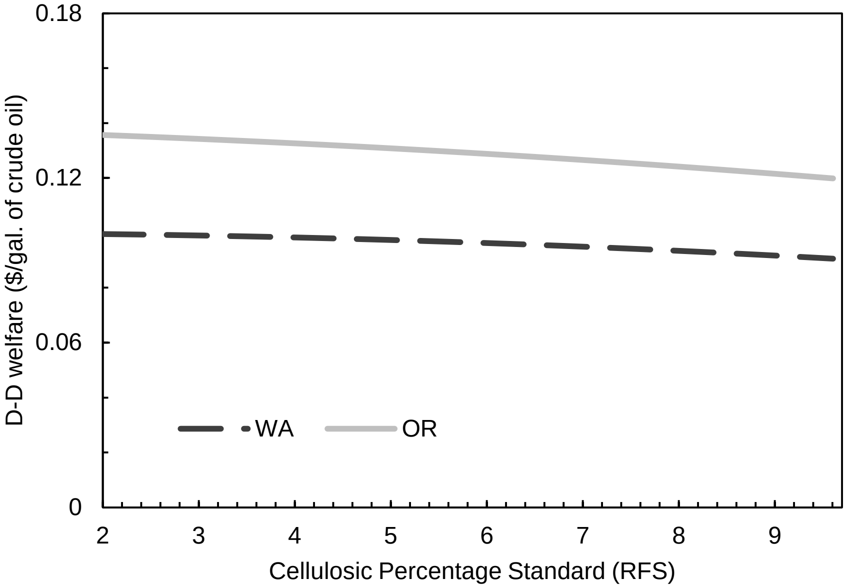

FIGURE 8. SIMULATED RESPONSE OF DOUBLE-DIVIDEND WELFARE (PER $/GAL. OF CRUDE OIL) TO CHANGES IN THE RFS

Appendix

A.1 Deriving welfare effects with a reduction in income tax.

Totally differentiate (9) and divide by the marginal change in the crude oil tax,

(A1) $$U_{t^o} = u_B B_{t^o} + u_X X_{t^o} + u_H H_{t^o} - c_E E_{Y^o} Y^o_{t^o}.$$

It will be useful to substitute the expression for marginal environmental damages in dollar terms from the use of crude oil into equation (A1),

(A2) $$D\left(Y^o\right) = \frac{1}{\lambda} c_E E_{Y^o},$$

where $D_{Y^o} < 0$.

Using the time constraint, we can derive dX / dt^o in terms of leisure and labor allocated to blended fuel production. Totally differentiating the time constraint, dividing by dt^o and re-arranging gives us:

(A3) $$X_{t^o} = -\left(L^b_{t^o} + H_{t^o}\right),$$

which expresses the change in composite good consumption from changes in the crude oil tax in terms of changes to leisure and labor for fuel blending.

To derive the total effect of the crude oil tax on blended fuel consumption, i.e. dB / dt^o, we recognize in equilibrium that, $B = Y^b$, so we can write

(A4) $$B_{t^o} = Y^b_{t^o} = Y^b_{Y^c} Y^c_{t^o} + Y^b_{Y^o} Y^o_{t^o} + Y^b_{L^b} L^b_{t^o}.$$

Finally, the crude oil tax influences the consumer's demand for leisure indirectly through changes in the blended fuel price and the labor tax,

(A5) $$H_{t^o} = H_{p^b} p^b_{t^o} + H_{t^l} \frac{dt^l}{dt^o},$$

To obtain dt^l / dt^o, we totally differentiate the government's budget constraint (8), dividing by dt^o, substituting dH / dt^o and re-arranging terms yields:

$$\text{(A6)} \qquad \frac{dt^l}{dt^o} = -\frac{Y^o + t^o\left({dY^o}\big/{dt^o} \right) + {dW}\big/{dt^o} - t^l H_{p^b}(dp^o / dt^o)}{T - H - t^l H_{t^l}},$$

Equation (A6) accounts for the reduction in income tax that can be financed by a change in crude oil tax while maintaining a balanced budget including the marginal gains in the waiver expenditure. Finally, substituting (A2) to (A6) into (A1) yields the expression in equation (10).

A.2 Deriving Welfare Effects With a Sales Tax

With a sales tax, the new optimality conditions for the consumer are:

$$\text{(A7)} \qquad \begin{aligned} \frac{\partial \mathcal{L}}{\partial B} &= -u_B + \lambda p^b = 0, \\ \frac{\partial \mathcal{L}}{\partial X} &= -u_X + \left(1 + t^x\right) = 0, \\ \frac{\partial \mathcal{L}}{\partial H} &= -u_H + \lambda w = 0, \\ \frac{\partial \mathcal{L}}{\partial \lambda} &= w\left(T - H\right) + G - p^b B - X. \end{aligned}$$

Simultaneously solving the first-order conditions leads to implicit demand functions of the form $B(p^b, t^x)$, $X(p^b, t^x)$, and $H(p^b, t^x)$.

The blended fuel sector only has one noticeable change. The inverse demand function for fuel is now a function of t^x, not t^l, as are the corresponding input demand functions.

The gross indirect utility function is specified as:

$$\text{(A8)} \qquad U\left(t^o, t^x\right) = u\left(B\left(p^b, t^x\right), X\left(p^b, t^x\right), H\left(p^b, t^x\right)\right) - c\left(E\left(Y^o\left(t^o, t^x\right)\right)\right).$$

Total differentiation of this function and dividing by dt^o yields:

$$\frac{dU}{dt^o} = u_B \frac{dB}{dt^o} + u_X \frac{dX}{dt^o} + u_H \frac{dH}{dt^o} - c' E_{Y^o} \frac{dY^o}{dt^o}, \tag{A9}$$

where $dX / dt^o = X_{p^b}(dp^b / dt^o) + X_{t^x}(dt^x / dt^o)$, and similar expressions apply for dB / dt^o and dH / dt^o. Substituting the damage function and the consumer's first-order conditions into (A9) yields:

$$\frac{1}{\lambda}\frac{dU}{dt^o} = p^b \frac{dB}{dt^o} + \left(1 + t^x\right)\frac{dX}{dt^o} + \frac{dH}{dt^o} - D\left(Y^o\right)\frac{dY^o}{dt^o}. \tag{A10}$$

We use equilibrium in the blended fuel market to substitute for dB / dt^o, and we decompose the change in leisure into equivalent changes in composite good consumption and blended fuel labor usage from the time constraint:

$$\frac{1}{\lambda}\frac{dU}{dt^o} = p^b \left(Y^b_{Y^c} \frac{dY^c}{dt^o} + Y^b_{Y^o} \frac{dY^o}{dt^o} + Y^b_{L^b} \frac{dL^b}{dt^o} \right) - \left(\frac{dL^b}{dt^o} + \frac{dX}{dt^o} \right) + \left(1 + t^x\right)\frac{dX}{dt^o} - D\left(Y^o\right)\frac{dY^o}{dt^o}. \tag{A11}$$

The Pigouvian effect and the residual Pigouvian effect remained unchanged, so we substitute in these expressions and decompose the change in composite good consumption:

$$\begin{aligned} \frac{1}{\lambda}\frac{dU}{dt^o} &= \left(D\left(Y^o\right) - p^b Y^b_{Y^o} \right)\left(-\frac{dY^o}{dt^o} \right) + p^b \left(Y^b_{Y^c} \frac{dY^c}{dt^o} + Y^b_{L^b} \frac{dL^b}{dt^o} \right) \\ &\quad + t^x \left(X_{t^o} + X_{t^x} \frac{dt^x}{dt^o} \right) - \frac{dL^b}{dt^o}. \end{aligned} \tag{A12}$$

Next to derive dt^x / dt^o, we totally differentiate the government's budget constraint, requiring the total change in government revenue to be equal to zero. Solving for dt^x / dt^o yields:

$$\frac{dt^x}{dt^o} = -\frac{Y^o + t^o \left(dY^o / dt^o \right) + dW / dt^o + t^x X_{t^o}}{X + t^x X_{t^x}}. \tag{A13}$$

From this expression, we can define the new M^x term, which measures the marginal change in deadweight loss:

(A14) $$M^x = \frac{-t^x X_{t^x}}{X + t^x X_{t^x}}.$$

The numerator of M^x is the loss composite good consumption to the consumer as a result of the tax, and the denominator is the marginal change in government revenue resulting from the tax. Substituting in M^x and the expression for dt^x / dt^o gives us our final expression:

(A15) $$\begin{aligned}\frac{1}{\lambda}\frac{dU}{dt^o} &= \left(D\left(Y^o\right) - p^b Y^b_{Y^o}\right)\left(-\frac{dY^o}{dt^o}\right) + p^b\left(Y^b_{Y^c}\frac{dY^c}{dt^o} + Y^b_{L^b}\frac{dL^b}{dt^o}\right)\\ &+M\left(Y^o + t^o\frac{dY^o}{dt^o} + \frac{dW}{dt^o}\right) - \left(\left(1+M\right)t^x X_{t^o} + \frac{dL^b}{dt^o}\right).\end{aligned}$$

A.3 Optimal tax derivation with revenues recycled to offset sales taxes

The first-order condition from the government's optimization problem of choosing the optimal Pigouvian tax is:

(A16) $$\begin{aligned}\frac{\partial\Omega(t^o)}{\partial t^o} &= \delta_{t^o} + n\frac{\partial\pi_i^b}{\partial t^o} + \pi^x_{t^o} + n\left(t^o\frac{\partial Y_i^o}{\partial t^o} + Y_i^o\right) + t^x X_{t^o}\\ &+n\frac{\partial W_i}{\partial t^o} - n\frac{\partial c}{\partial E}\frac{\partial E}{\partial Y_i^o}\frac{\partial Y_i^o}{\partial t^o} = 0.\end{aligned}$$

Solving this expression for t^o gives us a similar expression to the labor tax case, where $\hat{t}^{ox}$ denotes the optimal tax in the distortionary sales tax case:

(A17) $$\hat{t}^{ox} = \underbrace{\frac{\partial c}{\partial E}\frac{\partial E}{\partial Y_i^o}}_{A} - \frac{1}{n\left(\partial Y_i^o \big/ \partial t^o\right)}\left\{\delta_{t^o} + \underbrace{t^x X_{t^o} + n\frac{\partial W_i}{\partial t^o}}_{B}\right\}.$$

The optimal revenue-neutral tax solves the following equation:

(A18) $$\frac{\partial\tilde{\Omega}\left(t^o\right)}{\partial t^o} = \frac{\partial\Omega\left(t^o\right)}{\partial t^o} + \frac{\partial\Omega\left(t^o\right)}{\partial t^x}\frac{dt^x}{dt^o} = 0.$$

We already have the expression for $\partial\Omega(t^o)/\partial t^o$, but we still need the expression for $\partial\Omega(t^o)/\partial t^x$:

(A19) $$\frac{\partial\Omega}{\partial t^x} = \delta_{t^x} + t^x X_{t^x} + X + n\frac{\partial W_i}{\partial t^x} - n\frac{\partial c}{\partial E}\frac{\partial E}{\partial Y_i^o}\frac{\partial Y_i^o}{\partial t^x} + nt^o\frac{\partial Y_i^o}{\partial t^x}.$$

Substituting in $\partial\Omega(t^o)/\partial t^o$ and $\partial\Omega(t^o)/\partial t^x$ into the equation for $\partial\tilde{\Omega}(t^o)/\partial t^o$ and solving for t^o gives us the optimal revenue neutral tax:

(A20) $$\tilde{t}^{ox} = \frac{1}{\gamma^x}\hat{t}^{ox} - \frac{1}{n\left(\partial\tilde{Y}_i^o \middle/ \partial t^o\right)}\frac{dt^x}{dt^o}\Omega_{t^x},$$

where $\tilde{t}^{ox}$ is the optimal revenue-neutral crude oil tax in the presence of a distortionary sales tax and $\gamma^x \equiv (Y_{t^o}^o + Y_{t^x}^o(dt^x/dt^o))/Y_{t^o}^o$.