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Revenue-Neutral Pollution Taxes in the Presence of a Renewable Fuel Standard

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We assess the welfare implications of a revenue-neutral tax in the presence of two Renewable Fuel Standard (RFS) policies for cellulosic biofuels: the waiver credit and the input-ratio requirement. We extend the model of revenue-neutral taxation to allow for the taxation of a dirty input in an imperfectly competitive market while integrating RFS-specific policies. Simulations from Washington and Oregon indicate that a revenue-neutral tax raises welfare by 19%–21% but growth in cellulosic ethanol production is minimal, ranging from 0.6% to 1.5%. Pollution taxes, cellulosic ethanol production, and welfare are more responsive to the waiver credit than to the input-ratio requirement.

Key words: carbon tax, cellulosic biofuel, double-dividend

Introduction

A carbon tax is an effective and efficient means of reducing greenhouse gas (GHG) emissions (Tol, 2005), but considerable opposition exists for adopting such a program in the United States. However, when the revenue from a carbon tax is used to offset an existing distortionary tax policy, public support across political groups increases drastically (Amdur, Rabe, and Borick, 2014). Representative Delaney (2015) announced federal legislation taxing GHG emissions, using the revenues to offset corporate tax rate. There is growing support for imposing a revenue-neutral tax system to control GHG emissions at the state level:[1] California, New York, Massachusetts, Oregon, and Washington have proposed initiatives that imply a revenue-neutral carbon tax while reducing an existing distortionary tax.

In 2007, Congress passed the Energy Independence and Security Act (EISA), which imposes increasing consumption mandates through 2022 for several types of renewable fuel, designated as Renewable Fuel Standards (RFS). The act is a way to reduce GHG emissions by substituting for energy feedstock with a relatively lower emissions coefficient. The law mandates an increasingly important role for biofuels derived from cellulosic feedstocks such as woody crops or agricultural

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[1] A few countries have experimented with the use of revenue-neutral carbon taxes. The carbon tax implemented in British Columbia, Canada, in 2008 redistributed all tax revenues to consumers through offsetting tax reductions and transfers (Murray and Rivers, 2015). Norway implemented a carbon tax in 1991, with tax revenues redistributed to consumers through pension funds (Sumner, Bird, and Smith, 2009).

residue,[2] which are considered second-generation or advanced biofuels (conventional biofuels from sugar or starch are first-generation biofuels).[3]

There are two important RFS policies related to the cellulosic biofuel requirement: the input-ratio requirement, which imposes a lower bound on cellulosic fuel use in blended-fuel production, coupled with a waiver price, which can be used to circumvent the input-ratio requirement (CFR, 2011). These two instruments together led to no significant effect on cellulosic production—even when the input-ratio requirement was raised—because firms have the option to purchase waivers instead (Skolrud et al., 2016). Cellulosic fuel production increases when waiver prices increase (Skolrud et al., 2016). We are not aware of any study that considers a revenue-neutral tax with the RFS policies to incentivize cellulosic fuel production.

This article determines the effect on welfare and cellulosic fuel production from a revenue-neutral tax that targets crude oil use given the existing RFS policies related to the cellulosic biofuel requirements. We build a multisector general equilibrium model in which fossil fuel use is taxed and the tax revenue is used to offset a distortionary tax (either an income tax or a sales tax). Focusing on a crude oil tax allows us to determine the responsiveness of cellulosic ethanol production to 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, both of which are significant sources of cellulosic feedstocks for biofuels due to the abundance of agricultural land and woody biomass (Yoder et al., 2010). The two states provide contrasting sources of reduction in distortionary taxes: a state income tax in Oregon, which has no sales tax, and a sales tax in Washington, which has no state income tax.

The development of the cellulosic ethanol industry has fallen far short of expectations (Lade, Lin Lawell, and Smith, 2018; Olson, 2017). Until 2014, cumulative cellulosic biofuel production from agricultural residues amounted to approximately 300,000 gallons—far short of the expected 0.5 billion gallons expected in 2012 or the 1 billion gallons expected in 2013 (U.S. Environmental Protection Agency, 2016). A 2014 amendment to the RFS classified renewable compressed and liquefied natural biogas as cellulosic biofuel, increasing cellulosic production to approximately 33 million gallons. However, only 758,000 of those gallons came from agricultural residues (U.S. Environmental Protection Agency, 2016). In this paper, we develop a revenue-neutral tax model under a hypothetical long-run scenario in which cellulosic processing has advanced far enough that the production of cellulosic biofuels from agricultural and forestry sectors matches the current production achievable from biogas.

The double-dividend hypothesis states that when an environmental tax is implemented, the economy benefits in two ways: (i) a Pigouvian effect in the form of lower pollution and (ii) a revenue-recycling effect in the form of lower deadweight loss in a market in which a distortionary tax is decreased by the amount of pollution tax revenues raised (Pearce, 1991).[4] Bovenberg and de Mooij (1994) identified a third, negative effect, called the tax-interaction effect, in which pollution taxes that raise the price of a dirty good relative to the leisure price lead to less work and lower income tax revenue. Empirical studies show 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; Bovenberg and Goulder, 2002). In the theoretical models that delineate the three welfare effects, the tax considered is on the output itself. Gasoline production uses a mix of fuel sources. In the United States, ethanol is mixed with fossil fuel, which has a significantly higher emission coefficient. Thus, there is a need to explicitly model a revenue-neutral tax on a dirty input.

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[2] By 2022, the mandate calls for the consumption of approximately 16 billion gallons of cellulosic biofuel, a significant increase from the 33 million gallons produced in 2014 (FR2, 2015).

[3] Very few articles have examined the growth of the cellulosic biofuel industry (e.g., Skolrud et al., 2016; Miao, Hennessy, and Babcock, 2012). In contrast, there is an extensive literature on conventional biofuel production (see Rajagopal and Zilberman, 2007, for a survey of the literature).

[4] Bovenberg and Goulder (2002) provide an extensive survey of the literature.

This article makes theoretical and policy contributions. In the double-dividend literature, a Pigouvian effect, revenue-recycling effect, and tax-interaction effect are identified when a revenue-neutral tax is imposed (Parry, 1995; Parry and Bento, 2001; Bovenberg and Goulder, 2002; Goulder, 2013). 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. The effect is not new in the environmental taxation literature citep[refer to][p. S73]parry1995 but, to our knowledge, this is the first time its welfare effects have been explicitly quantified in a general equilibrium model.

We modify the general equilibrium model developed by Goulder, Parry, and Burtraw (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 applied to an input instead of to an output, there is a further decline in output in the polluting sector as long as the output effect dominates the substitution effect. When we include more intermediate sectors to understand the effect on feedstock supply, the tax-interaction effect is expanded. 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 is dependent on the sensitivity of the tax base to changes in the price of the polluting good.

In our simulations, we find that the marginal excess burden of income taxation exceeds the marginal excess burden of consumer sales taxation, leading to larger revenue-recycling and tax-interaction effects in Oregon than Washington. We also show that more stringent input-ratio requirements and higher waiver prices lead to lower revenue-neutral taxes because of a reduction in pollution where the latter policy has a more elastic responsiveness than the former policy. We find that the optimal revenue-neutral tax is approximately 65%–68% of the optimal Pigouvian tax, which is typical of estimates in the literature (Galinato and Yoder, 2010; Parry, 1995). Imposing a revenue-neutral tax increases welfare by 19% in Washington and 21% in Oregon. Cellulosic biofuel production increases slightly with the revenue-neutral tax, by 1.5% in Washington and 0.6% in Oregon.

Theoretical Model

Our baseline general equilibrium model includes a consumption sector, in which 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 first assume that only an income tax exists and is the main beneficiary from the pollution tax revenue. We relax this assumption later in the paper to accommodate a sales tax to model the Washington State case.

Consumption Sector

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

$$U(B,X,H,E) = u(B,X,H) - c(E), \quad (1)$$

where E is total emissions, $u(\bullet)$ is increasing and concave in all the arguments, and $c(\bullet)$ is an increasing convex function. Total emissions is increasing in the inputs used in the production of blended fuel, Y^b, such that $E = E(Y^b)$, where $E_{Y^b} > 0$.[5] Total income is derived from labor earnings

[5] Subscripts indicate partial derivatives.

and government transfers. The budget constraint is

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

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 $(T - H)$ 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 in equation (2) is an important driver of double-dividend results. The right side of equation (2) is similar to the consumer budget constraint of Goulder, Parry, and Burtraw (1997), but the left side differs in that the consumer does not pay for the tax on blended fuel directly. 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 maximizing the consumer's utility function in equation (1), subject to the budget constraint in equation (2), taking environmental quality as given, are

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

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

Composite-Good Sector

The composite good is produced using constant returns to scale technology, with labor as the only input, $X = L^x$. The composite-goods sector has three roles in the model. First, it serves as our numeraire good. Next, using the first-order condition in the profit maximization problem along with an output price of 1, the optimal wage rate is 1 (i.e., $w = 1$). Finally, we use the composite-good sector in the simulation section to calibrate the scale of the other sectors.

Blended-Fuel Sector

The blended-fuel production function for firm i is $Y_i^b(Y_i^c, Y_i^o, Y_i^e, L_i^b)$, where Y_i^c is cellulosic ethanol, Y_i^o is gasoline refined from crude oil, Y_i^e is corn ethanol, and L_i^b is labor used in the production of blended fuel.[6] Output is increasing and concave in all arguments. The production of cellulosic ethanol and gasoline are assumed to be exogenous in the base model. There are n firms in Cournot

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

competition in an oligopoly, such that the output price is endogenous.[7] We assume that the firm takes all input prices as exogenous.

Firms in the blended-fuel sector are subject to the requirements of the RFS, which mandates the use of multiple types of biofuels (CFR, 2011). The mandates are nested within multiple groups, differentiated by the capacity of each fuel type to reduce life-cycle GHG emissions compared to fossil fuels. The RFS caps the amount of conventional renewable fuel (i.e., corn ethanol) at 15 billion gallons after 2015, while the mandate for advanced biofuels, particularly cellulosic biofuel, continues to increase until 2022 (CFR, 2011). Rather than attempt to model the entire nested structure, we distill the mandates into two constraints: one that captures the role of corn ethanol and one that captures cellulosic ethanol. This simplification maintains the central feature of the RFS (i.e., increasing the use of renewable fuel in a way that requires more advanced biofuels as time progresses) but still allows analytical tractability.

The *total* renewable fuel mandate can be satisfied with either cellulosic ethanol or corn ethanol, but fuel blenders are required to use at least as much cellulosic ethanol as required by the cellulosic mandate. The cellulosic mandate is equal to the cellulosic ethanol percentage standard, Z^c, multiplied by the amount of gasoline refined from crude oil, Y_i^o, used by the fuel blender (i.e., $Z^c Y_i^o$). Since cellulosic ethanol is a much more expensive requirement on a per gallon basis than corn ethanol and the two are perfect substitutes, we can write the corn ethanol mandate as the difference between the total renewable mandate and the cellulosic mandate. Denoting the total renewable fuel mandate by R^T, the amount of corn ethanol purchased by the blender to satisfy the total mandate, defined as Y_i^e, is then given by $Y_i^e = R^T - Z^c Y_i^o$, or the remainder of the total mandate not satisfied by the cellulosic requirement. This definition encapsulates the fact that blenders will use as much corn ethanol as possible to satisfy the total mandate due to the relatively high cost of cellulosic ethanol. Total ethanol is $Y^E = Y^e + Y^c$.

The RFS also specifies an alternative means to satisfy the cellulosic requirement that is not available for any other type of biofuel. When cellulosic ethanol production is insufficient, firms can purchase waiver credits (CFR, 2011) to satisfy their RFS obligation at a price of g dollars per credit, where 1 credit is equivalent to 1 obligated gallon of cellulosic ethanol.[8] The RFS constraint is $Z^c Y_i^o = Y_i^c + W_i/g$, where W_i is the expenditure on waiver credits and g is the waiver credit price. The amount of cellulosic ethanol required by the RFS, $Z^c Y_i^o$, can be satisfied either by using a sufficient amount of cellulosic ethanol Y_i^c or by buying waiver credits, W_i/g.[9]

The firm chooses cellulosic ethanol, gasoline from crude oil, and labor to maximize profit,

$$
\begin{aligned}
\pi_i = {} & p^b \left(\sum_{j=1}^{n} Y_j{}^b \left(Y_j{}^c + Y_j^e, Y_j{}^o, L_j{}^b \right), t^l, w, G \right) Y_i^b \left(Y_i{}^c + Y_i^e, Y_i{}^o, L_i{}^b \right) \\
& - p^c Y_i{}^c - p^e Y_i^e - (p^o + t^o) Y_i{}^o - w L_i{}^b - W_i, \\
& \text{subject to: } Z^c Y_i^o = Y_i^c + \frac{W_i}{g}, \\
& Y_i^e = R^T - Z^c Y_i^o,
\end{aligned}
\tag{4}
$$

[7] We model the blended-fuel sector as an oligopoly, which is an appropriate assumption for both Washington and Oregon. The Pacific Northwest is largely served by five blended-fuel producers (oil refineries), and although collusive behavior has never been formally identified, the sector was investigated in 2008 by the Washington State Office of the Attorney General (2008) due to suspicions of price collusion.

[8] Cellulosic biofuel production is deemed insufficient when production fails to reach the amount mandated by the RFS (CFR, 2011).

[9] The waiver credit price is set by the U.S. Environmental Protection Agency as the higher value of $0.25 and the average annual wholesale price of gasoline per gallon minus $3 (CFR, 2011). Cellulosic biofuel is the only type of biofuel specified by the RFS to be eligible for waiver credits.

where $p^b(\bullet)$ is the inverse demand for blended fuel, p^c is the price of cellulosic ethanol, p^e is the price of corn ethanol, p^o is the price of gasoline refined from crude oil, and t^o is the per unit tax on gasoline use. The two constraints must be met for the firms to comply with the RFS mandates for total renewable fuel and cellulosic ethanol. Solving the maximization problem yields the following first-order conditions:[10]

$$
\begin{aligned}
\pi_{Y^c} &= p^b_{Y^b} Y^b_{Y^c} Y^b + p^b Y^b_{Y^c} - p^c + g = 0, \\
\pi_{Y^o} &= p^b_{Y^b} Y^b_{Y^o} Y^b + p^b Y^b_{Y^o} - (p^o + t^o) + Z^c (p^e - g) = 0, \\
\pi_{L^b} &= p^b_{Y^b} Y^b_{L^b} Y^b + p^b Y^b_{L^b} - w = 0.
\end{aligned}
\tag{5}
$$

Each equation shows the value of marginal product of each input equal to its marginal cost. For cellulosic ethanol, the value of marginal product includes the value of the waiver price. For gasoline refined from crude oil, marginal cost includes the oil price augmented by the tax and the effect from the interaction with both RFS standards, the magnitude of which is partially determined by the difference between the ethanol price and the cellulosic waiver credit price. The first-order conditions in equation (5) are solved to yield both the best response functions for each firm and the uncompensated input demand functions, given by given by $Y_i^c(\theta)$, $Y_i^o(\theta)$, and $L_i^b(\theta)$, where $\theta \equiv \{p^c, p^o, p^e, w, t^o, t^l, g, Z^c\}$.[11] The demand for corn ethanol is $Y_i^e = R^T - Z^c Y_i^o(\theta)$.

Equilibrium

The general equilibrium conditions that solve the model are derived using equations (3), (5), the market-clearing condition for labor,[12]

$$T = L^b + X + H. \tag{6}$$

demand for blended fuel equals its supply,

$$B\left(p^b, t^l, w, G\right) = Y^b\left(Y^c(\theta) + Y^e(\theta), Y^o(\theta), L^b(\theta)\right); \tag{7}$$

and the government budget constraint,

$$G = t^l(T - H) + t^o Y^o, \tag{8}$$

where $t^l(T - H)$ is the labor tax revenue and $t^o Y^o$ is the crude oil tax revenue.[13]

Revenue-Neutral Policy Change

Using implicit demand functions from the consumer's problem, equilibrium prices, and by recognizing that in equilibrium, $Y^b = B$, we can write the indirect utility function as

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

where p^b is the equilibrium price of blended fuel from equation (7).

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

[11] Since we assume that the market is not perfectly competitive, the input demands are no longer a function of the output price of blended fuel.

[12] Note that the units on the right side are in labor-time. Since X is a linear function of labor, it can be measured in the same labor-time units as T and H.

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

To assess the impact of a revenue-neutral policy change, where increases in the gasoline tax are offset by decreases in the distortionary labor tax to maintain the level of G, we totally differentiate equation (9), divide by the marginal change in the gasoline tax and simplify using the equilibrium conditions to derive[14]

$$\frac{1}{\lambda}\frac{dU}{dt^o} = \underbrace{\left(D\left(Y^b\right) - p^b Y^b_{Y^o}\right)\left(-\frac{dY^o}{dt^o}\right)}_{\text{Pigouvian effect}} + \underbrace{p^b\left(Y^b_{YE}\left(\frac{dY^c}{dt^o} + \frac{dY^e}{dt^o}\right) + Y^b_{L^b}\frac{dL^b}{dt^o}\right)}_{\text{Residual Pigouvian effect}}$$

(10)

$$+ \underbrace{M\left(Y^o + t^o\frac{dY^o}{dt^o}\right)}_{\text{Revenue-recyling effect}} \underbrace{- \left((1+M)t^l H_{t^o} + \frac{dL^b}{dt^o}\right)}_{\text{Interaction effect}},$$

where $D\left(Y^b\right) = (1/\lambda)c_E E_{Y^b}$ is the marginal environmental damage in dollar terms and $M \equiv t^l H_{t^l}/(T - H - t^l H_{t^l})$ is the marginal excess burden of taxation. The numerator of M represents the partial equilibrium welfare loss from an increase in the labor tax (i.e., the wedge distorting the wage rate from its market equilibrium, t^l, multiplied by the effect of the wedge on leisure). The denominator of M represents the partial equilibrium gain in government revenues resulting from the tax. We identify four welfare effects of the gasoline 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 environmental damages and marginal utility resulting from the impact of the gasoline tax on blended fuel. If the marginal social benefit, $D(Y^b) - p^b Y^b_{Y^o}$, is positive, the Pigouvian effect will be positive. Our version of the effect differs from its typical formulation in two ways. First, our effect includes the impact of imperfect competition, captured by the impact on the price of blended fuel induced by the change in blended-fuel production resulting from the gasoline tax. In perfect competition, the output change from one firm would have no effect on the output price. The second departure is the input-oriented tax, targeted at only one of the dirty inputs. This is a slight change 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.[15]

The residual Pigouvian effect that we find only occurs with a pollution tax on just one of the dirty inputs and not output. It represents the change in marginal utility from a change in blended-fuel production resulting from changes in total ethanol from cellulosic and corn feedstocks (the $Y^b_{YE}\left((dY^c/dt^o) + (dY^e/dt^o)\right)$ term) and labor (the $Y^b_{L^b}(dL^b/dt^o)$ term). If the output effect dominates the substitution effect, so that the marginal effect of the gasoline tax rate on corn and 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 gasoline tax leads to lower use of all inputs in the blended-fuel sector, leaving less blended fuel for consumption.

The revenue-recycling effect represents the gain in efficiency from using the gasoline tax revenue to offset the labor tax, which reduces deadweight loss in the labor market. This effect is positive under our assumptions.

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, $t^l H_{t^o}$; increases the deadweight loss, $t^l M H_{t^o}$;[16] and reduces labor in the blended-fuel sector, dL^b/dt^o.[17] When the gasoline tax increases and less

[14] To ensure revenue neutrality, we use the fact that $dG/dt^0 = 0$ and $dt^l/dt^o \neq 0$, as shown in the online supplement (www.jareonline.org).

[15] See Parry (1995, pp. S73–S76) for an example of intermediate good taxation and the resulting Pigouvian effect.

[16] Note that $t^l H_{t^o}$ is the change in leisure from the crude oil tax multiplied by the wedge. Multiplying this change by the marginal excess burden of labor taxation, M, makes this term the marginal change in deadweight loss.

[17] In the case in which blended fuel and leisure are complements, the tax-interaction effect becomes an efficiency gain, as discussed in Goulder, Parry, and Burtraw (1997).

blended fuel is available to the consumer, labor shifts from the blended-fuel sector toward leisure and composite-good-producing labor. The overall tax-interaction effect is negative.

Optimal Tax Derivation

The government considers the welfare of producers, consumers, and other parties negatively affected by pollution.[18] The government maximizes the sum of consumer surplus, profits from the blended-fuel and composite-good sectors, and tax revenues, minus the disutility from pollution by choosing an optimal tax on gasoline refined from crude oil,

$$\Omega(t^o) = \max_{t^o} \delta(t^o) + n\pi_i^b(t^o) + \tau(t^o) - c(E(t^o)), \tag{11}$$

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 $\tau(t^o) \equiv nt^oY_i^o + t^l(T - H)$, and profits in the composite-good sector are π^x. After manipulating the first-order condition, the Pigouvian tax is

$$\hat{t}^o = \underbrace{c_E E_{Y^b}}_{A} - \frac{1}{nY_{t^o}^o}\left\{\delta_{t^o} - \underbrace{t^l H_{t^o}}_{B}\right\}. \tag{12}$$

The Pigouvian tax, $\hat{t}^o$, is decomposed into three components.[19] The first component, A, represents the marginal damages from blended fuel. The second component is the marginal effect of the gasoline tax on consumer surplus, δ_{t^o}. In partial equilibrium, these are the only components. In general equilibrium, the optimal Pigouvian tax also includes the marginal effect on government revenue, B, scaled by the impact on crude oil use resulting from the gasoline tax.

To calculate the optimal revenue-neutral tax,[20] we allow the labor tax to be a function of the gasoline 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,

$$\tilde{t}^o = \frac{1}{\gamma}\hat{t}^o - \frac{1}{n\tilde{Y}_{t^o}^o}\frac{dt^l}{dt^o}\Omega_{t^l}, \tag{13}$$

where $\tilde{Y}_{t^o}^o \equiv Y_{t^o}^o + Y_{t^l}^o(dt^l/dt^o)$ is the marginal change in gasoline use from the gasoline tax under revenue-neutral taxation, $\gamma \equiv \tilde{Y}_{t^o}^o/Y_{t^o}^o$ is the ratio of marginal changes in gasoline use from the gasoline tax under revenue-neutral and Pigouvian taxation, $\Omega_{t^l} \equiv \delta_{t^l} + nt^oY_{t^l}^o + T - H - t^lH_{t^l} - nc_E E_{Y^o}Y_{t^l}^o$ is the marginal impact on social welfare from the labor tax, and $dt^l/dt^o = -(Y^o + t^o(dY^o/dt^o) - t^lH_{p^b}(dp^o/dt^o))/(T - H - t^lH_{t^l})$ is the reduction in income tax that can be financed by a change in gasoline tax while maintaining a balanced budget. Thus, the revenue-neutral tax is a fraction of the Pigouvian tax minus a term that captures the social welfare loss from labor taxation weighted by the change in the labor tax induced by the change in crude oil tax while maintaining a balanced budget. 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 gasoline as a result of the gasoline tax when the labor tax is variable ($\tilde{Y}_{t^o}^o$) and the change in gasoline usage as a result of the gasoline tax when the labor tax is fixed ($Y_{t^o}^o$). The sign and magnitude of γ depend on the ratio of the impact of the labor tax on gasoline divided by the impact of the gasoline

[18] Since the pollution taxes reflect the shadow value of an externality, they are not considered simple transfers and are included in the welfare function. Including pollution tax revenues in the maximization of the welfare function shows the total value society places on pollution damages from crude oil use.

[19] Since our policy does not tax all polluting inputs, our Pigouvian tax in equation (12) would be lower than a Pigouvian tax that accounts for all polluting inputs.

[20] See the online supplement for complete derivation.

tax on gasoline production multiplied by the reduction in the income tax that can be financed from gasoline tax revenues. For a complementary input relationship between labor and gasoline in the production of blended fuel, $Y^o_{t^l}(dt^l/dt^o) > 0$, implying that $\gamma > 1$.

Extending the Baseline Model

We extend the baseline model in two ways. First, we allow for the revenue from the gasoline 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. By including intermediate sectors, we analyze the extent to which labor market distortions are exacerbated or mitigated outside of the direct effect on the industries subject to the environmental tax.

The Double-Dividend with a Sales Tax

There are two differences in the setup of the model with a sales tax instead of income tax. First, the consumer's budget constraint now takes the form $p^b B + (1+t^x)X = w(T-H) + G$, where t^x is the per unit tax on the composite good. The labor tax is now removed from the right side of the budget constraint. The second difference is the government's budget constraint, which is now $G = t^x X + t^o Y^o$.

The change in welfare given a change in gasoline tax based on our four effects is[21]

$$(14)\quad \begin{aligned} \frac{1}{\lambda}\frac{dU}{dt^o} = & \underbrace{\left(D\left(Y^b\right) - p^b Y^b_{Y^o}\right)\left(-\frac{dY^o}{dt^o}\right)}_{\text{Pigouvian effect}} + \underbrace{p^b\left(Y^b_{Y^E}\left(\frac{dY^c}{dt^o} + \frac{dY^e}{dt^o}\right) + Y^b_{L^b}\frac{dL^b}{dt^o}\right)}_{\text{Residual Pigouvian effect}} \\ & \underbrace{+ M^x\left(Y^o + t^o\frac{dY^o}{dt^o}\right)}_{\text{Revenue-recyling effect}} \underbrace{- \left((1+M^x)t^x X_{t^o} + \frac{dL^b}{dt^o}\right)}_{\text{Interaction effect}}, \end{aligned}$$

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 partial equilibrium welfare loss from an increase in the composite-goods tax, and the denominator is the partial equilibrium gain in government revenues 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 the absolute magnitudes of the revenue-recycling effect and tax-interaction effects to be larger compared to the sales tax case.

To derive the Pigouvian tax, we use a similar government objective function as equation (11), except the tax revenue expression is now $\tau(t^o) = nt^o Y^o + t^x X$:[22]

$$(15)\quad \hat{t}^{ox} = \underbrace{c_E E_{Y^b}}_{A} - \frac{1}{nY^o_{t^o}}\left\{\delta_{t^o} + \underbrace{t^x X_{t^o}}_{B}\right\}.$$

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.

[21] See the online supplement for proof.
[22] See the online supplement for proof.

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

$$\tilde{t}^{ox} = \frac{1}{\gamma^x}\hat{t}^{ox} - \frac{1}{n\tilde{Y}^o_{t^o}}\frac{dt^x}{dt^o}\Omega_{t^x}, \tag{16}$$

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 gasoline use from the gasoline tax under revenue-neutral and Pigouvian taxation, $dt^x/dt^o = -(Y^o + t^o(dY^o/dt^o) + t^x X_{t^o})/(X + t^x X_{t^x})$ is the reduction in the sales tax that can be financed by a change in gasoline tax while maintaining a balanced budget, and $\Omega_{t^x} \equiv \delta_{t^x} + t^x X_{t^x} + X - nc_E E_{Y^o} Y^o_{t^l} + nt^o Y^o_{t^x}$ 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 are also interested in the downstream impacts of taxes to the sectors that supply cellulosic feedstock, most notably the agricultural and forestry sectors. Production of cellulosic ethanol occurs in 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. The production function in each sector is $Y^s = Y^s(K^s, L^s, R^s)$, $\forall\, s = a, f$, 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,

$$\begin{aligned} p^s Y^s_{K^s}(K^s, L^s, R^s) - r &= 0,\\ p^s Y^s_{L^s}(K^s, L^s, R^s) - w &= 0,\\ p^s Y^s_{R^s}(K^s, L^s, R^s) - m &= 0, \end{aligned} \tag{17}$$

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

The cellulosic-refining sector uses feedstock output from the agricultural and forest sectors along with capital and labor to produce cellulosic ethanol. The production function is $Y^c = Y^c(K^c, L^c, Y^a, Y^f)$, which is also increasing and concave in all arguments. Assuming perfect competition, the first-order conditions are

$$\begin{aligned} p^c Y^c_{K^c}(K^c, L^c, Y^a, Y^f) - r &= 0,\\ p^c Y^c_{L^c}(K^c, L^c, Y^a, Y^f) - w &= 0,\\ p^c Y^c_{Y^a}(K^c, L^c, Y^a, Y^f) - p^a &= 0,\\ p^c Y^c_{Y^f}(K^c, L^c, Y^a, Y^f) - p^f &= 0, \end{aligned} \tag{18}$$

where p^c is the output price for cellulosic ethanol. Each condition equates the value of marginal product to its input price.

Equilibrium entails that the systems of equations in (17) and (18) hold along with the following market-clearing conditions:

$$Y^s(K^s, L^s, R^s) = Y^s(p^c, p^a, p^f, r, w),\ \forall\, s = a, f, \tag{19}$$

equating cellulosic-feedstock production to feedstock demand in the cellulosic-refining sector;

$$Y^c(K^c, L^c, Y^a, Y^f) = Y^c(p^c, p^o, p^e, w, r, t^o, t^l, g, Z^c), \tag{20}$$

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

$$Y^b(p^c, p^o, p^e, w, r, t^o, t^l, g, Z^c) = B(p^b, w, t^l, G), \tag{21}$$

equating total blended-fuel production to blended-fuel demand from the consumer. Additionally, the markets for capital, land, and labor clear:

(22)
$$\begin{aligned}\bar{K} &= K^a + K^f + K^c + K^b,\\ \bar{R} &= R^a + R^f,\\ T &= L^a + L^f + L^c + L^b + L^x + H.\end{aligned}$$

The labor-market-clearing equation is amended to allow labor in the new sectors in the economy.

The welfare effects from a revenue-neutral policy are

(23)
$$\begin{aligned}\frac{1}{\lambda}\frac{dU}{dt^o} =& \underbrace{\left(D\left(Y^b\right) - p^b Y^b_{Y^o}\right)\left(-\frac{dY^o}{dt^o}\right)}_{\text{Pigouvian effect}} + \underbrace{p^b\left(Y^b_{YE}\left(\frac{dY^c}{dt^o} + \frac{dY^e}{dt^o}\right) + Y^b_{L^b}\frac{dL^b}{dt^o}\right)}_{\text{Residual Pigouvian effect}}\\ &+ \underbrace{M\left(Y^o + t^o\frac{dY^o}{dt^o}\right)}_{\text{Revenue-recycling effect}} - \underbrace{\left((1+M)t^l H_{t^o} + \frac{dL^b}{dt^o} + \frac{dL^a}{dt^o} + \frac{dL^f}{dt^o} + \frac{dL^c}{dt^o}\right)}_{\text{Interaction effect}}.\end{aligned}$$

The first difference comes with the change in labor in the composite-good sector brought about by a change in the gasoline tax. With more sectors, each sector will experience corresponding labor changes 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 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 is 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 are determined using the full set of optimality conditions from each sector to account for the general equilibrium change.

Numerical Simulation

We simulate the model for Washington State and Oregon to contrast the effect of a revenue-neutral 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. All of our simulations are short-run simulations since we do not have a dynamic stock that changes in the model. Given our limited data and information regarding future potential changes in technology, we only conduct comparative static effect of the RFS policy, under the assumption that technology and production costs remain constant over time.

Functional Forms, Parameters, and Simulation Procedure

We employ constant elasticity of substitution (CES) production functions in each sector because they are less restrictive than Cobb–Douglas and more tractable than a fully flexible functional form such as the translog.[23] In the agricultural and forestry sectors, this implies that

(24)
$$Y^s = A^s\left(\sum\nolimits_{i=\{K,L,R\}} d^s_i (i^s)^{\rho^s}\right)^{1/\rho^s}, \forall\, s = \{a, f\},$$

[23] The popularity of the CES functional form in calibration studies of environmental economics ensures a high degree of comparability across studies (see, e.g., Goulder, Parry, and Burtraw, 1997; Bovenberg and Goulder, 1996; Parry and Bento, 2001).

where A^s is a calibrated scaling parameter; d_K^s, d_L^s, and d_R^s are calibrated share parameters such that $d_K^s + d_L^s + d_R^s = 1$; and the elasticity of substitution is $\sigma^s \equiv 1/(1-\rho^s)$.

For the cellulosic-feedstock-refining and blended-fuel sectors, we use nested CES production functions to allow for elasticities of substitution to vary between pairs of inputs. In the cellulosic-refining sector, we model cellulosic material from agriculture and forestry sources as close substitutes, but we specify a complementary relationship between the labor/capital input pair and the agricultural/forestry cellulosic material pair. We treat the blended-fuel sector in a similar manner, with high degrees of substitutability between gasoline refined from crude oil and cellulosic ethanol but low substitutability between fuel inputs and labor and capital. In keeping with our long-run technology assumption, we allow the cellulosic-feedstock-refining sector to supply the blended-fuel sector with an unrestricted amount of cellulosic ethanol. The functional forms for the cellulosic-refining and blended-fuel sectors are

(25)

$$Y^c = A^c\left((\alpha^c)\left(\Sigma_{j=\{K^c,L^c\}} d_j^c(j)^{\rho^c_{K^cL^c}}\right)^{\rho^c/\rho^c_{K^cL^c}} + (1-\alpha^c)\left(\Sigma_{j=\{Y^a,Y^f\}} d_j^c(j)^{\rho^c_{Y^aY^f}}\right)^{\rho^c/\rho^c_{Y^aY^f}}\right)^{1/\rho^c},$$

(26)

$$Y_i^b = A^b\left((\alpha^b)\left(\Sigma_{j=\{K^b,L^b\}} d_j^b(j)^{\rho^b_{K^bL^b}}\right)^{\rho^b/\rho^b_{K^bL^b}} + (1-\alpha^b)\left(\Sigma_{j=\{Y^c,Y^o\}} d_j^b(j)^{\rho^b_{Y^cY^o}}\right)^{\rho^b/\rho^b_{Y^cY^o}}\right)^{1/\rho^b},$$

where α^c, α^b, A^c, A^b, d_j^c for $j = \{K^c, L^c, Y^a, Y^f\}$ and d_j^b for $j = \{K_i^b, L_i^b, Y_i^c, Y_i^o\}$ are calibrated parameters, $\sigma_j^c = 1/(1-\rho_j^c)$ for $j = \{K^cL^c, Y^aY^f\}$ is the elasticity of substitution between the input pairs in j for the production of cellulosic ethanol, and $\sigma_j^b = 1/(1-\rho_j^b)$ for $j = \{K^bL^b, Y^cY^o\}$ is the elasticity of substitution between the input pairs in j for the $j = \{K^bL^b, Y^cY^o\}$ production of blended fuel.

The utility function is CES, where $u(B,X,H) = (d_B B^\rho + d_X X^\rho + d_H H^\rho)^{1/\rho} - \delta E$. Following Galinato and Yoder (2010), the marginal disutility of emissions, δ, is set to \$25/ton of CO_2. Emissions incorporates the total emissions from using gasoline refined from crude oil, cellulosic ethanol, and corn ethanol, $E = \gamma^o Y^o + \gamma^e Y^e + \gamma^c Y^c$, where $\gamma^o, \gamma^e, \gamma^c$ are the emission coefficients for gasoline refined from crude oil, cellulosic ethanol, and corn ethanol, respectively. These values are expressed in CO_2 equivalents and are equal to 0.0089 tons of CO_2/gal (U.S. Energy Information Administration, 2016), 0.0036 tons of CO_2/gal, and 0.0071 tons of CO_2//gal (CFR, 2011) for gasoline refined from crude oil, cellulosic ethanol, and corn ethanol, respectively. The share parameters of the utility function and each production function are calibrated and the elasticities of substitution come from the literature (see Table 1). We follow Goulder, Parry, and Burtraw (1997) in assuming that leisure time, H, is 1.4 times work time, which we set to 40 hours/week for 50 weeks/year in accordance with the U.S. Bureau of Labor Statistics (2013b) definition.

To calibrate the share parameters of the production functions, we use the method outlined by Howitt (1995), calibrating the share parameters of the production functions by simultaneously solving each system of first-order conditions as a function of baseline data. For example, we can write the ratio of any two first-order conditions from a CES production function as $\frac{d_i^f}{d_j^f} = \frac{(j^f)^{\rho^f-1} p_i}{(i^f)^{\rho^f-1} p_j}$ for $i, j = K, L, R$, where p_i is the price for input i, $i = K, L, R$. Combining two of the ratio conditions and the condition that $d_K^f + d_L^f + d_R^f = 1$ identifies the share parameters. The scaling parameters are recovered from each production function once the share parameters are solved and data for inputs and output levels are used.[24] The systems of first-order conditions are solved for production-

[24] This method of identifying share parameters is sensitive to the underlying input quantity and price observations; using data from different years would influence share parameter values.

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		
Total	0.50	Assumption
Labor/capital	0.50	Assumption
Agricultural cellulose/forestry cellulose	$\rightarrow \infty$	Assumption
Blended fuel sector		
Total	$\rightarrow 0$	Assumption
Gasoline/cellulosic ethanol	$\rightarrow \infty$	Assumption
Labor, capital	0.50	Assumption
Composite good sector	0.50	Assumption
Consumer's utility function	0.11	Banks, Blundell, and Lewbel (1997)

Notes: [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.

share parameters as a function of baseline data, which include quantities, prices, and elasticities of substitution from Tables 1 and 2.[25]

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's emphasis on agriculture over forestry; Oregon's emphasis is the opposite. Washington employs more labor and capital in agriculture and less labor and capital in forestry than Oregon. Washington 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 U.S. Environmental Protection Agency reported national production of cellulosic ethanol equal to 33 million gallons (U.S. Environmental Protection Agency, 2016). To provide a starting point for our hypothetical long-run scenario, we assume that Washington and Oregon could account for a share of national cellulosic ethanol production equal to their respective shares of national petroleum consumption. This is consistent with the findings of Yoder et al. (2010), who discuss the considerable advantage held by Oregon and Washington in the long-run potential for cellulosic feedstock production. In 2012, Washington's share of national petroleum consumption was 2%, while Oregon's share was 0.9% (U.S. Energy Information Administration, 2013c,d), 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 from forest residues in 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.[26] 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;

[25] This method highlights the value of using the CES functional form: The system of first-order conditions in each sector is enough to uniquely identify all parameters of the production function (Howitt, 1995). For further details on the calibration process, refer to Skolrud et al. (2016).

[26] Sims et al. (2010) indicate a range of 110–270 liters per ton (l/t) for conversion from switchgrass to ethanol, and a range of 125–300 l/t for forestry residues. We use the midpoints of each range for our conversion factor. Dutta, Daverey, and Lin (2014) derive a similar estimate that fits within the range of Sims et al. (2010).

Table 2. Parameter Values

Parameters	State WA	State OR	Units	Source
Inputs				
Agricultural labor[a]	1.16	0.34	Full-time laborers[g]	U.S. Bureau of Labor Statistics (2013b,a)
Agricultural capital[b]	3.79	1.56	Tractors/equipment	U.S. Department of Agriculture (2013c)
Agricultural resources	1,096	493.1	Acres	U.S. Department of Agriculture (2013b)
Forestry labor[c]	3.17	1.87	Full-time laborers	U.S. Bureau of Labor Statistics (2013b,a)
Forestry capital[d]	52.82	29.67	Capital units[h]	Washington State Department of Natural Resources (2012), Gale et al. (2012)
Forestry resources	17,257	11,840	Acres	Washington State Department of Natural Resources (2012), Gale et al. (2012)
Cellulosic refining labor	22.6	10.17	Full-time laborers	U.S. Bureau of Labor Statistics (2013b,a)
Cellulosic refining capital	342.64	154.19	Capital units	Washington Research Council (2012)
Fuel blending labor[d]	1,130	508	Full-time laborers	U.S. Bureau of Labor Statistics (2013b,a)
Fuel blending capital[f]	17,132	7,709	Capital units	Washington Research Council (2012)
Gasoline refined from crude oil	5.67	2.55	Gallons (billions)	U.S. Energy Information Administration (2013a,c)
Composite good labor	15,035	12,098	Full-time laborers	U.S. Bureau of Labor Statistics (2013b,a)
Composite good capital	174,157	159,495	Capital units	U.S. Department of Agriculture (2013c), Washington State Department of Natural Resources (2012), Gale et al. (2012)
Composite good resources	27.65	36.57	Acres (millions)	U.S. Department of Agriculture (2013b), Washington State Department of Natural Resources (2012), Gale et al. (2012)
Outputs				
Cellulosic feedstock, agriculture[i]	6,575	2,959	Tons	Sims et al. (2010), U.S. Energy Information Administration (2013a,c)
Cellulosic feedstock, forestry[i]	5,879	2,645	Tons	Sims et al. (2010), U.S. Energy Information Administration (2013a,c)
Cellulosic ethanol[j]	660	297	Gallons (thousands)	FR2 (2015), U.S. Energy Information Administration (2013a,c)
Blended fuel	2.6	1.17	Gallons (billions)	U.S. Energy Information Administration (2013a,c)
Composite good[k]	11.98	8.34	$ (billions)	U.S. Department of Agriculture (2013a), Washington State Department of Natural Resources (2012), Gale et al. (2012)
Prices				
Wage rate	36,296	33,596	$/year	U.S. Bureau of Labor Statistics (2013b,a)
Rental rate of capital[l]	8,680	8,680	$/year	U.S. Department of Agriculture (2014)
Land resource price	215	130	$/acre	U.S. Department of Agriculture (2013c)
Cellulosic feedstock, agriculture	65	65	$/dry ton	University of Kentucky Center for Crop Diversification (2013)
Cellulosic feedstock, forestry	52.27	52.27	$/dry ton	Gale et al. (2012)
Cellulosic ethanol	2.35	2.35	$/gallon	Governors' Biofuels Commission (2011)
Corn ethanol	1.82	1.82	$/gallon	U.S. Department of Agriculture (2018)
Gasoline	2.24	2.24	$/gallon	U.S. Energy Information Administration (2013b)
Final blended fuel[m]	3.76	3.76	$/gallon	U.S. Energy Information Administration (2013d)

Table 3. Welfare Effects

Effects	State WA	State OR
Welfare effects		
($/gal of gasoline)		
Revenue-recycling	$0.17	$0.21
Pigouvian	$0.11	$0.15
Residual Pigouvian	−$0.03	−$0.03
Interaction	−$0.15	−$0.21
Sum of effects	$0.10	$0.12
Aggregate social welfare effects		
(percentage increase in social welfare from no-tax baseline)		
Pigouvian taxation	10%	12%
Revenue neutral taxation	19%	21%

Washington State Department of Natural Resources, 2012). The agricultural land requirement is based on an estimated yield of 6 dry tons of switchgrass per acre (University of Kentucky Center for Crop Diversification, 2013). We assume capital–land and labor–land ratios are the same as those used in state-level agriculture and forestry production.

We use numerical optimization to solve for the optimal tax rates for both the revenue unconstrained and revenue constrained cases in our model. When we examine the revenue-constrained case, we form a system of 28 equations in 28 unknowns, consisting of the first-order conditions from each sector (equations 3, 5, 17, and 18); the two RFS constraints in the blended-fuel-sector maximization problem (equation 5); the market-clearing conditions for capital, labor, and resource inputs (equation 22); outputs (equations 19–21); and the government budget constraint (equation 8). In the revenue-unconstrained case we have one less equation because we do not impose the government's budget constraint. We calculate optimal taxes by using numerical approximations of the optimal tax expressions in equations (12) and (13) for Oregon and equations (15) and (16) for Washington.[27]

Simulation Results

Table 3 summarizes the welfare effects from an optimal revenue-neutral tax.[28] We find that, as expected from our theory, the revenue-recycling and Pigouvian effects are positive, while the residual Pigouvian and interaction effects are negative. The revenue-recycling effect is larger in Oregon than in Washington. Therefore, simulation results for our two states suggest that the efficiency gain from revenue-neutral taxation through the reduction of deadweight loss is higher in Oregon, where an income tax is imposed, as opposed to the sales tax in Washington. Similarly, the absolute value of the tax-interaction effect is larger in Oregon than in 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 4%–5% of welfare change. A small negative residual Pigouvian effect indicates that the output effects slightly dominate substitution effects.

Washington and Oregon consume approximately 2.6 billion gallons and 1.17 billion gallons of fuel annually. Imposing a revenue-neutral tax yields $261 million and $164 million in annual welfare gains for Washington and Oregon, respectively. We find welfare growth in Washington on

[27] Derivatives are approximated numerically using finite difference methods (see Judd, 1998).

[28] Each of these welfare effects is composed of derivatives whose values are estimated using the entire system of 28 optimality and market-clearing conditions with finite difference approximation. Each derivative expression is re-evaluated with the new endogenous prices and quantities at every step of the estimation.

Table 4. Optimal Taxes at Baseline Parameter Values ($/gal of gasoline)

	State	
	WA	**OR**
Pigouvian	$0.28	$0.34
Revenue neutral	$0.19	$0.22

Table 5. Change in Fuel Production (millions of gallons)

	State	
2012 Baseline Values	**WA**	**OR**
Blended fuel	2,604.11	1,171.85
Cellulosic fuel	0.66	0.30
With Pigouvian Tax (% change from baseline)		
Blended fuel	−6.94%	−3.91%
Cellulosic fuel	3.01%	1.10%
With Revenue Neutral Tax (% change from baseline)		
Blended fuel	−5.58%	−3.13%
Cellulosic fuel	1.47%	0.58%

the order of 10% from Pigouvian taxation and 19% from revenue-neutral taxation relative to a no-tax baseline. Oregon welfare improvements are 12% and 21% for Pigouvian and revenue-neutral taxation, respectively. These results are similar to Goulder, Parry, and Burtraw (1997), who find net welfare gains of 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 (see Table 4).[29] Our results indicate that the revenue-neutral tax is approximately 65%–68% 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). The Pigouvian tax is slightly higher than the marginal environmental damage ($0.25/gal of gasoline), which is the result of general equilibrium effects on consumer surplus and government revenue, as shown in equation (12).

The Pigouvian and revenue-neutral tax regimes result in a change in blended fuel and cellulosic fuel production (see Table 5). 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 where there is a minimal increase in cellulosic ethanol production by 0.6%–1.5%. Here, the firm substitutes away from the now relatively more expensive gasoline toward cellulosic ethanol, but the substitution effect is not large enough to overcome the decline in production of blended fuel from the output effect.

With the calibrated parameters held fixed, we vary the values of the RFS percentage mandate and the waiver price. Values for the RFS percentage mandate are varied from their 2014 level through the proposed level in 2022. We also consider waiver prices ranging from a baseline level of $0.78/credit to $2.23/credit in 5-cent increments.[30]

Figures 1 and 2 illustrate the responsiveness of the Pigouvian tax and Figures 3 and 4 show the responsiveness of the revenue-neutral tax to both RFS policies. Both tax structures are much more sensitive to changes in the waiver price than to changes in the cellulosic percentage standard.

[29] For Washington, we use the Pigouvian and revenue-neutral tax expressions associated with a distortionary tax on the composite good (equations 12 and 13, respectively); for Oregon, we use tax expressions associated with a distortionary tax on labor income (equations 15 and 16, respectively).

[30] The waiver price in 2012 was $0.78/credit, while $2.23/credit implies a maximum retail gasoline price of $5.23/gal based on the relationship discussed in footnote 9.

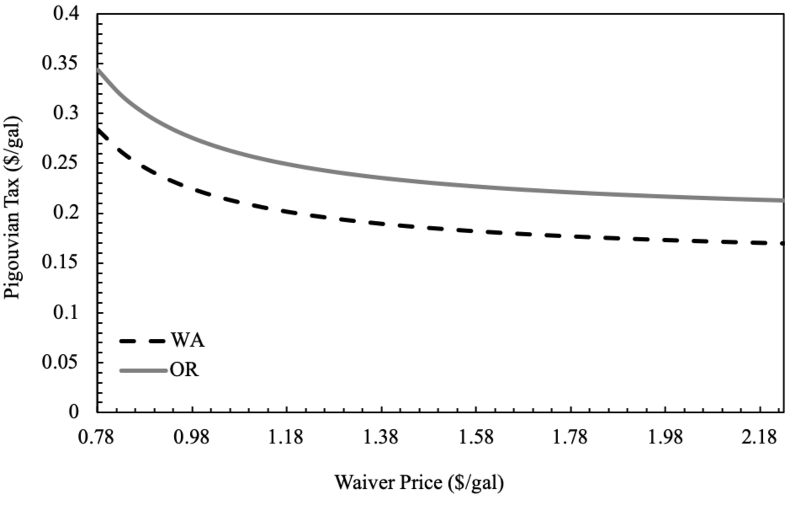

Figure 1. Simulated Response of the Pigouvian Tax to Changes in the Waiver Price

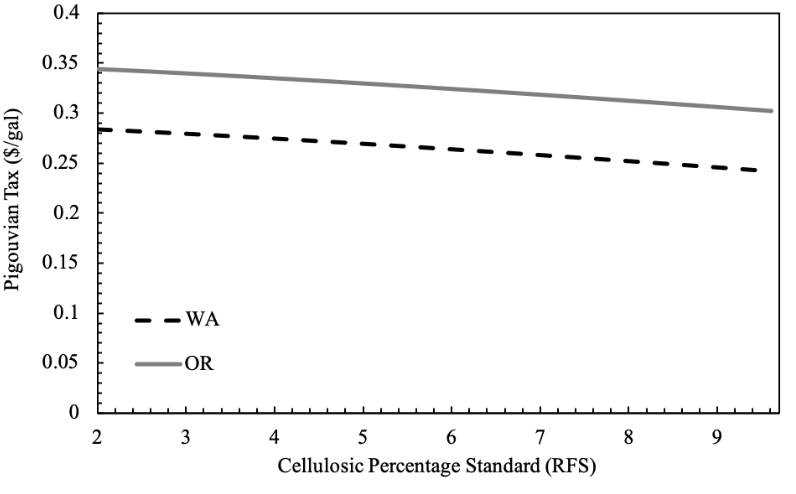

Figure 2. Simulated response of the Pigouvian tax to changes in the RFS

In the Pigouvian tax case, the average elasticity measuring its responsiveness to the waiver price is −0.48 for Washington and −0.47 for Oregon, whereas the responsiveness to the percentage standard is just −0.006 and −0.005 for Washington 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 and Oregon, respectively. When the waiver price increases, producers use more cellulosic ethanol, decreasing gasoline 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. The trend in Figures 1–4 is consistent across states; the slope of each curve varies only slightly. Interestingly, a consistent pattern for Washington 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 the type of distortionary tax in the economy.

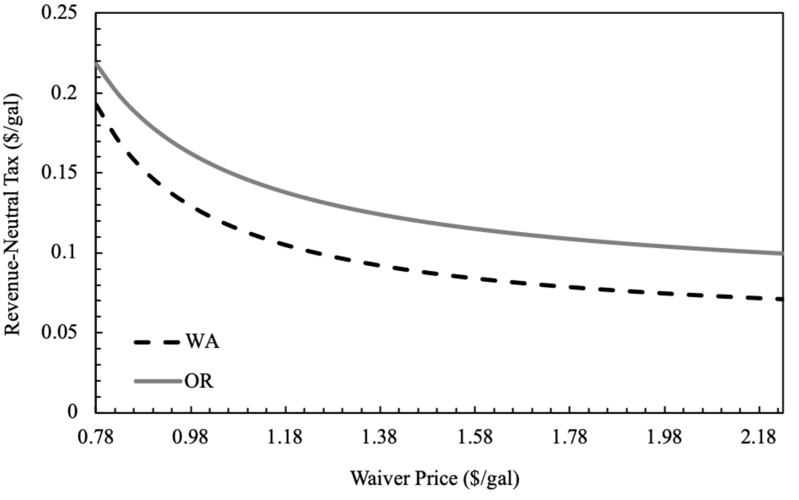

Figure 3. Simulated Response of the Revenue-Neutral Tax to Changes in the Waiver Price

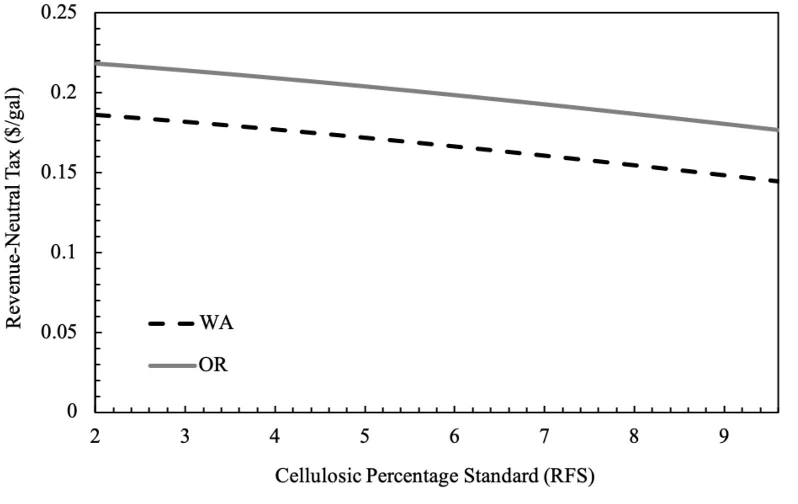

Figure 4. Simulated Response of the Revenue-Neutral Tax to Changes in the RFS

In Figures 5 and 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 than to changes in the RFS. The impact on ethanol production from changes in the percentage standard is negligible because of producers' ability to purchase waiver credits (Figure 6).

Figures 7 and 8 examine changes in marginal 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. The net effect is a decreasing influence of the waiver price 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.

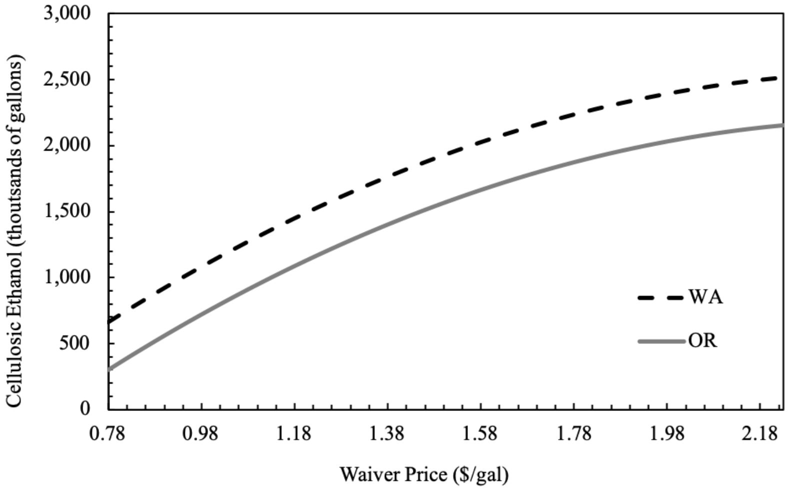

Figure 5. Simulated Response of Cellulosic Ethanol Production to Changes in the Waiver Price

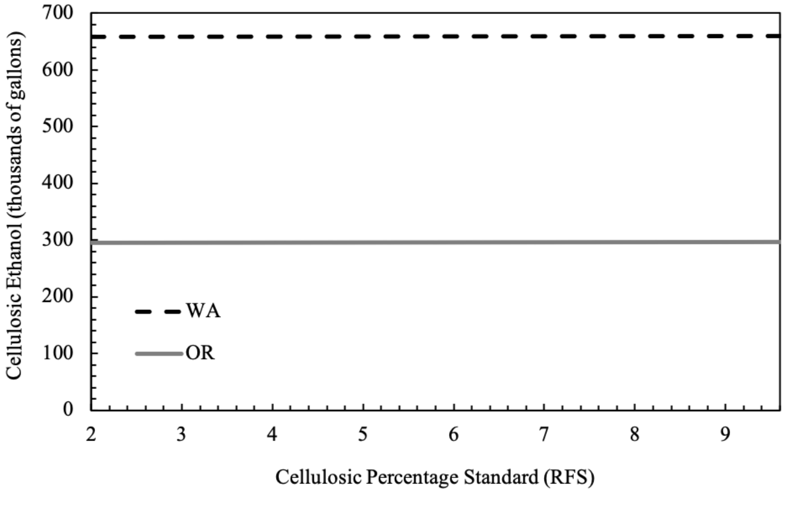

Figure 6. Simulated Response of Cellulosic Ethanol Production to Changes in the RFS

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 multisector general equilibrium model that includes (i) a fuel-production sector subject to both RFS requirements and a revenue-neutral tax on gasoline refined from crude oil usage and (ii) a consumer sector that values consumption of blended fuel and environmental quality. The focus on taxing crude oil allows us to measure the responsiveness of other renewable fuels—such as cellulosic ethanol—given such a tax.

We show theoretically that tax revenues can be recycled into a nonlabor 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 present evidence that the RFS waiver credit price affects the optimal tax rate, while the RFS percentage standard for cellulosic biofuel has only a limited effect. With a suitable increase

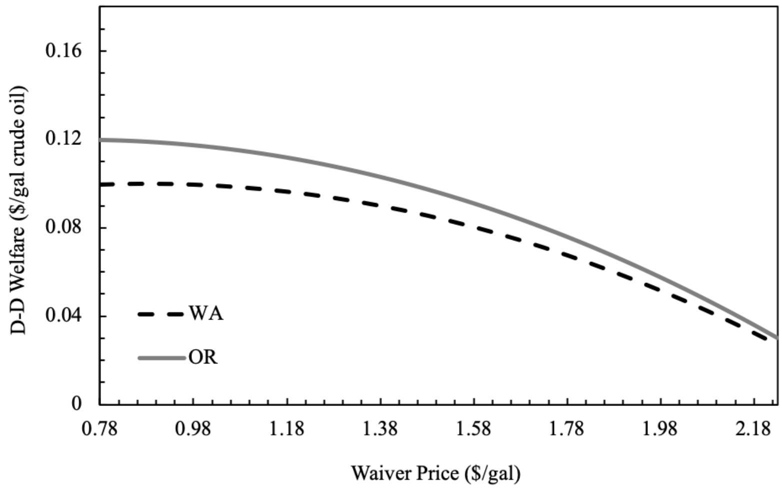

Figure 7. Simulated Response of Double-Dividend Welfare (per $/gal of gasoline) to Changes in the Waiver Price

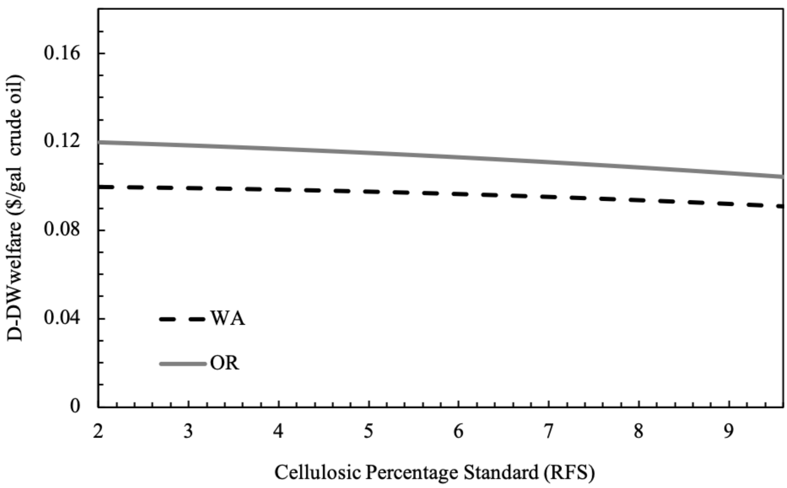

Figure 8. Simulated Response of Double-Dividend Welfare (per $/gal of gasoline) to Changes in the RFS

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 effects on production if the waiver price is low. This result echoes previous research by Skolrud et al. (2016) highlighting the vulnerability of the burgeoning cellulosic ethanol industry to waiver credit prices that are low enough to provide a less expensive pathway to RFS compliance. Finally, we note that an increase in the waiver price will decrease the marginal welfare impact of revenue-neutral taxation because of lower emissions when using more cellulosic ethanol.

Our work has a few limitations, mostly related to the assumptions that must be made to analyze a young cellulosic ethanol industry with limited publicly available data. Specifically, we assume that input ratios are similar between the agriculture and forestry sectors, and we are forced to assume several elasticities of substitution for sectors with missing data. To analyze the issue at a regional level, we must also make an assumption about the production of cellulosic biofuel feedstocks where they have yet to be fully established. However, we are confident that the data proxies used in our analysis do not serve to mitigate the magnitude or importance of our primary results concerning the effect of an increasing cellulosic mandate or a change to the cellulosic waiver credit price. Finally, we focus only on short-run analysis, assuming that technology and production costs remain the same over time. With more data in the future, one might be able to extend the model to incorporate dynamic changes to cost or technology.

Our results show that the RFS policies affect the optimal choice of revenue-neutral taxes. A high waiver credit price or a larger renewable fuel standard reduces the optimal revenue-neutral pollution tax rate. By imposing a revenue-neutral tax on fossil fuel usage in fuel production, social welfare increases significantly, by 19%–21%. The revenue-neutral tax induces a reduction in pollution and a slight increase of 0.6%–1.5% in cellulosic production. Skolrud and Galinato (2017) show that increasing a tax on crude oil and using the revenues to subsidize cellulosic fuel production leads to an overall increase in social welfare of just 1%, but cellulosic fuel production grows by 28%–238%. The ideal mechanism to return tax revenues is then dependent on the objectives of the policy maker; to grow the cellulosic fuel industry, the preferable choice is to tax crude oil and subsidize cellulosic fuel production. But if the policy maker's objective is to increase overall welfare, it would be preferable to reduce distortionary taxes instead.

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Online Supplement: Revenue-Neutral Pollution Taxes in the Presence of a Renewable Fuel Standard

Tristan D. Skolrud and Gregmar I. Galinato

Deriving Welfare Effects with a Reduction in Income Tax

Using implicit demand functions from the consumer's problem, equilibrium prices, and the fact that $Y^b = B$ in equilibrium, we can write the indirect utility function as

$$U(t^o,t^l) = u(Y^b(t^o,t^l,Z^c,g),X(p^b,t^l),H(p^b,t^l)) - c[E(Y^b(t^o,t^l,Z^c,g))]. \tag{S1}$$

To assess the impact of a revenue-neutral policy change, where increases in the gasoline tax are offset by decreases in the distortionary labor tax, we totally differentiate equation (S1), dividing by the marginal change in the gasoline tax:

$$\frac{dU}{dt^o} = u_B\frac{dY^b}{dt^o} + u_X\frac{dX}{dt^o} + u_H\frac{dH}{dt^o} - c'E_{Y^b}\frac{dY^b}{dt^o}. \tag{S2}$$

The gasoline tax influences the consumer's demand for leisure indirectly through changes in the blended-fuel price, wage rate, and the labor tax; specifically:

$$\frac{dH}{dt^o} = H_{p^b}\frac{dp^b}{dt^o} + H_{t^l}\frac{dt^l}{dt^o}, \tag{S3}$$

where similar expressions apply for dX/dt^o and dB/dt^o. It will be useful to substitute the expression for marginal environmental damages from the use of gasoline into equation (S2). Partially differentiating the utility function, equation 1, with respect to total emissions, and substituting in the emissions production function $E = E(Y^b)$ and the equilibrium expression for Y^b, we obtain marginal environmental damage in terms of dollars:

$$D(Y^b) = \frac{1}{\lambda}cE_{Y^b}, \tag{S4}$$

where $D_{Y^b} < 0$. Now we can substitute equation (S4) and the first-order conditions of the consumer, equations 3, into equation (S2) to obtain

$$\frac{1}{\lambda}\frac{dU}{dt^o} = p^b\frac{dY^b}{dt^o} + \frac{dX}{dt^o} + \left(1-t^l\right)\frac{dH}{dt^o} - D\left(Y^b\right)\frac{dY^b}{dt^o}. \tag{S5}$$

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

$$\frac{dT}{dt^o} = \frac{dX}{dt^o} + \frac{dL^b}{dt^o} + \frac{dH}{dt^o} = 0, \tag{S6}$$

implying that

$$\frac{dX}{dt^o} = -\left(\frac{dL^b}{dt^o} + \frac{dH}{dt^o}\right), \tag{S7}$$

which expresses the change in composite-good consumption from changes in the gasoline tax in terms of changes to leisure and labor for fuel blending. Substituting equation (S7) into equation (S5) yields

$$\text{(S8)} \qquad \frac{1}{\lambda}\frac{dU}{dt^o} = p^b\frac{dY^b}{dt^o} - \left(\frac{dL^b}{dt^o} + \frac{dH}{dt^o}\right) + (1-t^l)\frac{dH}{dt^o} - D(Y^b)\frac{dY^b}{dt^o}.$$

To decompose the effect of the gasoline tax on utility, we need to further decompose the dH/dt^o term. This will require the derivation of dt^l/dt^o, or the reduction in the labor tax that can be financed with the gasoline tax. To obtain this expression, we totally differentiate the governmentâĂŹs budget constraint, $G = t^l(T-H) + t^oY^o$, maintaining a balanced budget:

$$\text{(S9)} \qquad dG = dt^l(T-H) + t^l(dT - dH) + dt^oY^o + t^odY^o = 0.$$

Dividing by dt^o and substituting dH/dt^o from equation (S3) yields:

$$\text{(S10)} \qquad \frac{dt^l}{dt^o}(T-H) - t^l\left(H_{p^b}\frac{dp^b}{dt^o} + H_{t^l}\frac{dt^l}{dt^o}\right) + Y^o + t^o\frac{dY^o}{dt^o} = 0.$$

Rearranging terms and solving for dt^l/dt^o gives us

$$\text{(S11)} \qquad \frac{dt^l}{dt^o} = -\frac{Y^o + t^o\left(dY^o/dt^o\right) - t^lH_{t^o}}{T - H - t^lH_{t^l}}$$

where $H_{t^o} = H_{p^b}\left(dp^b/dt^o\right)$. Now we are ready to explicitly define each of the effects associated with the double-dividend hypothesis. First, we need to examine the dY^b/dt^o term, capturing the total effect of the gasoline tax on blended fuel. Expanding the derivative, we can write

$$\text{(S12)} \qquad \frac{dY^b}{dt^o} = Y^b_{YE}\left(\frac{dY^c}{dt^o} + \frac{dY^e}{dt^o}\right) + Y^b_{Y^o}\frac{dY^o}{dt^o} + Y^b_{L^b}\frac{dL^b}{dt^o}$$

Substituting this expression into equation (S8) yields

$$\text{(S13)} \qquad \begin{aligned} \frac{1}{\lambda}\frac{dU}{dt^o} &= p^b\left(Y^b_{YE}\left(\frac{dY^c}{dt^o} + \frac{dY^e}{dt^o}\right) + Y^b_{Y^o}\frac{dY^o}{dt^o} + Y^b_{L^b}\frac{dL^b}{dt^o}\right) \\ &\quad - \left(\frac{dL^b}{dt^o} + \frac{dH}{dt^o}\right) + \left(1-t^l\right)\frac{dH}{dt^o} - D\left(Y^b\right)\frac{dY^b}{dt^o}. \end{aligned}$$

Next, we gather the dY/dt^o terms that comprise the Pigouvian effect (PE) defined as $PE \equiv \left(D\left(Y^b\right) - p^bY^b_{Y^o}\right)\left(-dY^o/dt^o\right)$. The revenue-recycling (RE) and tax-interaction (IE) effects require further decomposition of the leisure effect dH/dt^o. Substituting equation (S3) into equation (S13) yields

$$\text{(S14)} \qquad \begin{aligned} \frac{1}{\lambda}\frac{dU}{dt^o} &= PE + p^b\left(Y^b_{YE}\left(\frac{dY^c}{dt^o} + \frac{dY^e}{dt^o}\right) + Y^b_{L^b}\frac{dL^b}{dt^o}\right) \\ &\quad - \left(\frac{dL^b}{dt^o} + \frac{dH}{dt^o}\right) + (1-t^l)\left(H_{t^o} + H_{t^l}\frac{dt^l}{dt^o}\right). \end{aligned}$$

Substituting in the expression for dt^l/dt^o from equation (S11) and simplifying yields

$$\text{(S15)} \qquad \begin{aligned} \frac{1}{\lambda}\frac{dU}{dt^o} &= PE + p^b\left(Y^b_{YE}\left(\frac{dY^c}{dt^o} + \frac{dY^e}{dt^o}\right) + Y^b_{L^b}\frac{dL^b}{dt^o}\right) \\ &\quad - \frac{dL^b}{dt^o} - t^l\left(H_{t^o} + H_{t^l}\left(-\frac{Y^o + t^o\left(dY^o/dt^o\right) - t^lH_{t^o}}{T - H - t^lH_{t^l}}\right)\right) \end{aligned}$$

Define M as the marginal change in deadweight loss to describe these effects:

(S16) $$M \equiv \frac{t^l H_{t^l}}{T - H - t^l H_{t^l}}$$

Substituting M into equation (S15) yields the following expression:

(S17) $$\begin{aligned}\frac{1}{\lambda}\frac{dU}{dt^o} =& PE + \underbrace{p^b\left(Y^b_{Y^E}\left(\frac{dY^c}{dt^o} + \frac{dY^e}{dt^o}\right) + Y^b_{L^b}\frac{dL^b}{dt^o}\right)}_{RPE} \\ & + \underbrace{M\left(Y^o + t^o\frac{dY^o}{dt^o}\right)}_{RE} - \underbrace{(1-M)t^l H_{t^o + \frac{dL^b}{dt^o}}}_{IE}.\end{aligned}$$

Deriving the Optimal Revenue-Neutral Tax

The derivation of the optimal double-dividend tax follows the same steps as the Pigouvian tax derivation. However, when calculating the optimal tax, we need to allow the labor tax to be a function of the crude oil tax, so that the government's objective function can be written $\Omega = \Omega(t^o, t^l(t^o))$. Partially differentiating with respect to t^o gives us the first-order condition $\tilde{\Omega}_{t^o} = \Omega_{t^o} + (dt^l/dt^o)\Omega_{t^l} = 0$. Expressions for Ω_{t^o} and (dt^l/dt^o) have been derived previously, but we need an expression for Ω_{t^l}:

(S18) $$\frac{\partial \Omega}{\partial t^l} = \delta_{t^l} + nt^o Y^o_{t^l} + T - H - t^l H_{t^l} - n\frac{\partial c}{\partial E}\frac{\partial E}{\partial Y^o_i}\frac{\partial Y^o_i}{\partial t^l}$$

Combining this equation with the first-order condition from the Pigouvian tax derivation gives us

(S19) $$\begin{aligned}\frac{\partial \tilde{\Omega}(t^o)}{t^o} =& \delta_{t^o} + nt^o\frac{dY^o_i}{dt^o} - t^l H_{t^o} - n\frac{\partial c}{\partial E}\frac{\partial E}{\partial Y^o_i}\frac{\partial Y^o_i}{\partial t^o} \\ & + \frac{dt^l}{dt^o}\left(\delta_{t^l} + nt^o Y^o_{t^l} + T - H - t^l H_{t^l} - n\frac{\partial c}{\partial E}\frac{\partial E}{\partial Y^o_i}\frac{\partial Y^o_i}{\partial t^l}\right) = 0.\end{aligned}$$

We can factor out t^o to obtain the following:

(S20) $$\tilde{t}^o = \frac{\partial c}{\partial E}\frac{\partial E}{\partial Y^o_i} - \frac{1}{n\frac{\partial \tilde{Y}^o_i}{\partial t^o}}\left(\delta_{t^o} - t^l H_{t^o} + \frac{dt^l}{dt^o}\left(\delta_{t^l} + T - H - t^l H_{t^l}\right)\right),$$

where $\partial \tilde{Y}^o_i/\partial t^o \equiv \partial Y^o_i/\partial t^o + (\partial Y^o_i/\partial t^l)(dt^l/dt^o)$. Defining γ as $\gamma \equiv (\partial \tilde{Y}^o_i/\partial t^o)/(\partial Y^o_i/\partial t^o)$ and substituting in $\hat{t}^o$ will allow us to simplify the above expression further:

(S21) $$\gamma\tilde{t}^o = \gamma\frac{\partial c}{\partial E}\frac{\partial E}{\partial Y^o_i} + \left(\hat{t}^o - \frac{\partial c}{\partial E}\frac{\partial E}{\partial Y^o_i}\right) - \frac{\gamma}{n\frac{\partial \tilde{Y}^o_i}{\partial t^o}}\frac{dt^l}{dt^o}(\gamma_{t^l} + T - H - t^l H_{t^l}).$$

We can simplify the expression for $\tilde{t}^o$ even further by substituting in our expression for Ω_{t^l}, which yields equation 13 in the text:

(S22) $$\tilde{t}^o = \frac{1}{\gamma}\hat{t}^o - \frac{1}{n\left(\partial \tilde{Y}^o_i \big/ \partial t^o\right)}\frac{dt^l}{dt^o}\Omega_{t^l}.$$

Deriving Welfare Effects with a Sales Tax

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

$$\text{(S23)}\qquad \begin{aligned} \frac{\partial \mathscr{L}}{\partial B} &= -\, u_B + \lambda p^b = 0 \\ \frac{\partial \mathscr{L}}{\partial X} &= -\, u_X + (1+t^x) = 0 \\ \frac{\partial \mathscr{L}}{\partial H} &= -\, u_H + \lambda w = 0 \\ \frac{\partial \mathscr{L}}{\partial \lambda} &= w(T-H) + G - p^b B - X. \end{aligned}$$

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 (recognizing again that $B = Y^b$in equilibrium)

$$\text{(S24)}\qquad U(t^o,t^x) = u(Y^b(Y^c,Y^o,L^b),X(p^b,t^x),H(p^b,t^x)) - c(E(Y^o(t^o,t^x))).$$

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

$$\text{(S25)}\qquad \frac{dU}{dt^o} = u_B \frac{dY^b}{dt^o} + u_X \frac{dX}{dt^o} + u_H \frac{dH}{dt^o} - c' E_{Y^o} \frac{dY^o}{dt^o},$$

$dX/dt^o = X_{p^b}(dp^b/dt^o) + X_{t^x}(dt^x/dt^o)$, and similar expressions apply for dH/dt^o. Substituting the damage function and the consumer's first-order conditions into equation (S25) yields

$$\text{(S26)}\qquad \frac{1}{\lambda}\frac{dU}{dt^o} = p^b \frac{dY^b}{dt^o} + (1+t^x)\frac{dX}{dt^o} + \frac{dH}{dt^o} - D(Y^o)\frac{dY^o}{dt^o}.$$

We decompose the change in leisure into equivalent changes in composite-good consumption and blended-fuel labor usage from the time constraint:

$$\text{(S27)}\qquad \begin{aligned} \frac{1}{\lambda}\frac{dU}{dt^o} &= p^b \left(Y^b_{Y^c}\frac{dY^c}{dt^o} + Y^b_{Y^o}\frac{dY^o}{dt^o} + Y^b_{L^b}\frac{dL^b}{dt^o} \right) \\ &\quad - \left(\frac{dL^b}{dt^o} + \frac{dX}{dt^o} \right) + (1+t^x)\frac{dX}{dt^o} - D(Y^o)\frac{dY^o}{dt^o}. \end{aligned}$$

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

$$\text{(S28)}\qquad \begin{aligned} \frac{1}{\lambda}\frac{dU}{dt^o} &= \left(D(Y^o) - p^b Y^b_{Y^o} \right)\left(-\frac{dY^o}{dt^o} \right) + p^b \left(Y^b_{Y^c}\frac{dY^c}{dt^o} + Y^b_{L^b}\frac{dL^b}{dt^o} \right) \\ &\quad + t^x \left(X_{t^o} + X_{t^x}\frac{dt^x}{dt^o} \right) - \frac{dL^b}{dt^o}. \end{aligned}$$

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 0. Solving for dt^x/dt^o yields

$$\text{(S29)}\qquad \frac{dt^x}{dt^o} = -\frac{Y^o + t^o\,(dY^o/dt^o) + t^x X_{t^o}}{X + t^x X_{t^x}}$$

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

$$M^x = \frac{-t^x X_{t^x}}{X + t^x X_{t^x}}. \tag{S30}$$

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:

$$\begin{aligned}\frac{1}{\lambda}\frac{dU}{dt^o} &= (D(Y^o) - p^b Y^b_{Y^o})\left(-\frac{dY^o}{dt^o}\right) + p^b\left(Y^b_{Y^c}\frac{dY^c}{dt^o} + Y^b_{L^b}\frac{dL^b}{dt^o}\right) \\ &+ M\left(Y^o + t^o\frac{dY^o}{dt^o}\right) - \left((1+M)t^x X_{t^o} + \frac{dL^b}{dt^o}\right).\end{aligned} \tag{S31}$$

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

$$\frac{\partial\Omega(t^o)}{\partial t^o} = \delta_{t^o} + n\frac{\partial\pi^b_i}{\partial t^o} + \pi^x_{t^o} + n\left(t^o\frac{\partial Y^o_i}{dt^o} + Y^o_i\right) + t^x X_{t^o} n\frac{\partial c}{\partial E}\frac{\partial E}{\partial Y^o_i}\frac{\partial Y^o_i}{\partial t^o} = 0 \tag{S32}$$

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:

$$\hat{t}^{ox} = \underbrace{\frac{\partial c}{\partial E}\frac{\partial E}{\partial Y^o_i}}_{A} - \frac{1}{n\left(\partial Y^o_i / \partial t^o\right)}\left\{\delta_{t^o} + \underbrace{t^x X_{t^o}}_{B}\right\}. \tag{S33}$$

The optimal revenue-neutral tax solves the following equation:

$$\frac{\partial\tilde{\Omega}(t^o)}{\partial t^o} = \frac{\partial\Omega(t^o)}{\partial t^o} + \frac{\partial\Omega(t^o)}{dt^x}\frac{dt^x}{dt^o} = 0. \tag{S34}$$

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

$$\frac{\partial\Omega}{\partial t^x} = \delta_{t^x} + t^x X_{t^x} + X - n\frac{\partial c}{\partial E}\frac{\partial E}{\partial Y^o_i}\frac{\partial Y^o_i}{\partial t^x} + nt^o\frac{\partial Y^o_i}{\partial t^x}. \tag{S35}$$

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:

$$\tilde{t}^{ox} = \frac{1}{\gamma^x}\hat{t}^{ox} - \frac{1}{n\left(\partial\tilde{Y}^o_i / \partial t^o\right)}\frac{dt^x}{dt^o}\Omega_{t^x}, \tag{S36}$$

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

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